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The Natural Resources Conservation Service (NRCS) is a USDA agency that works with landowners through conservation planning and assistance to benefit the soil, water, air, plants, and animals for productive lands and healthy ecosystems. Working in nearly every county in the Nation, NRCS employees understand local resource concerns and challenges to assist with conservation solutions that last. Land stewardship by private landowners is critical to the health of our Nation's environment. Science and technology are critical to good conservation. NRCS experts from many disciplines come together to help landowners conserve natural resources in efficient, smart and sustainable ways. NRCS succeeds through partnerships, working closely with individual farmers and ranchers, landowners, local conservation districts, government agencies, Tribes, Earth Team volunteers and many other people and groups that care about the quality of America's natural resources. More information about the NRCS is at [www.nrcs.usda.gov](http://www.nrcs.usda.gov).



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- Assess the nutritional needs of Americans
- Sustain a competitive agricultural economy
- Enhance the natural resource base and the environment, and
- Provide economic opportunities for rural citizens, communities, and society as a whole.

More information about the ARS is at [www.ars.usda.gov](http://www.ars.usda.gov).



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The American Forage and Grassland Council (AFGC) is an international organization made up of 22 affiliate councils in the United States and Canada with a total individual membership of about 2,500. Its primary objective is to advance the use of forage as a prime resource for feed and for natural resource conservation. Its members represent the academic community, producers, private industry, institutes and foundations. Together, they unite in a common cause to develop the forage industry and promote the profitable production and sustainable utilization of quality forage and grasslands. More information about AFGC is at [www.afgc.org](http://www.afgc.org).



C. JERRY NELSON

Conservation Outcomes from Pastureland and Hayland Practices Assessment, Recommendations, and Knowledge Gaps

# Conservation Outcomes from Pastureland and Hayland Practices

## Assessment, Recommendations, and Knowledge Gaps



C. JERRY NELSON, EDITOR



**On the cover:** Beef stockers grazing a mixed species pasture in a scenic area of Vermont. Photo is courtesy of NRCS.

Nelson, C.J. (ed.) 2012. *Conservation Outcomes from Pastureland and Hayland Practices: Assessment, Recommendations, and Knowledge Gaps*. Allen Press, Lawrence, Kansas.

Printed by  
Allen Press, Inc.  
810 E. 10th Street  
Lawrence, KS 66044

Funding was provided by the USDA Natural Resources Conservation Service, with cooperation from the USDA Agricultural Research Service, through a partnership with the American Forage and Grassland Council in support of the Conservation Effects Assessment Project.



The expressed goal of this synthesis is to inform deliberations of managers and policymakers regarding the current effectiveness and potential improvements to pastureland and hayland conservation programs. As such, this synthesis represents a scientific assessment that was reached independently of the current position or policy of the US Department of Agriculture or the United States government.

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ISBN 978-0-9849499-2-2

Print Date: December 2012

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# Conservation Outcomes from Pastureland and Hayland Practices

Assessment, Recommendations, and Knowledge Gaps



The Conservation Effects Assessment Project (CEAP) is a multiagency effort to quantify scientifically the environmental outcomes of conservation practices used by private landowners.

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This effort  
will assist in  
advancing the  
broader values  
of pastures and  
hay fields”

## FOREWORD

Forages and grasslands have long been important for the food supply of humans, mainly through ruminant animals and wildlife. Early on, production of food and farm income was sometimes accomplished at the expense of the environment. Early in the 20th century, while U.S. agriculture felt the brunt of the depression and the dust bowl, strong public interest emerged in conservation and new concepts of grassland agriculture. The Soil Conservation Service was formed, new regulations were enacted, and cost-share programs were established to assist farmers with conservation goals. Now, early in the 21st century, the USA is recognizing that agriculture, and especially grassland agriculture, provides multiple services to humankind.

The pastureland conservation effects assessment project (CEAP) is a multiagency effort by the Natural Resources Conservation Service (NRCS), National Institute of Food and Agriculture (NIFA), Agricultural Research Service (ARS), and National Resources Inventory (NRI) to quantify environmental effects of conservation practices used by landowners participating in selected USDA programs. In 2008, writing teams of university, ARS, and NRCS scientists were assembled to address the science base for conservation practice standards for 1) pasture and hayland planting, 2) prescribed grazing, 3) harvest management, and 4) nutrient management. Integrated syntheses incorporating socioeconomic concerns were also made. The goal was to inform NRCS, scientific and outreach communities, and especially policy advisors of the current status. The literature synthesis itself is a landmark contribution on effects of conservation practices on environmental goods and services derived from U.S. pastures and haylands.

The writing teams are commended for their detailed literature search, thorough review, and salient assessment of the science base for conservation practices. Without their due diligence and persistent efforts the assessment would not be as detailed or effective. It is not easy to compare conservation data from experiments using different species, soils and climates, yet common features were teased out and assessed. In some cases solid themes emerged, while in others there was not enough research data to evaluate, fully, which was duly pointed out. Each team provided conclusions and pointed to new directions. Thanks are due to the ARS (Matt A. Sanderson) and NRCS (Leonard W. Jolley) for agency liaison and to C. Jerry Nelson for professional and editorial leadership on the project.

As an organization that encourages economically and environmentally sound forage agriculture, the American Forage and Grassland Council is pleased to be a part of this major effort. There is a strong need for mechanisms that help producers and agencies work together to apply science in ways that improve both incomes and the environment. It is also critical to discern research needs to fill knowledge gaps and support more effective management decisions. This authoritative book also provides the foundational framework to move toward even more effective practice criteria for conservation and a strong science base to undergird them.

We know this effort will assist in advancing the broader values of pastures and hay fields. It will also better equip landowner clients and agency personnel to develop, implement, and utilize management practices that best provide an adequate income for the producer while enhancing the environment and providing other ecosystem services to improve the quality of life for everyone.

Bob Hendershot, AFGC President (2010–2011)

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Bill Tucker, AFGC President (2008–2009)

Gary Pederson, AFGC President (2007–2008)

## PREFACE

Pastureland and hayland are known to reduce soil erosion and play important roles in land stewardship on diversified farms. The Dust Bowl of the 1930s stimulated the concept of grassland agriculture: an on-farm system in which pastures and hay fields play significant roles in crop rotations and soil conservation. In addition, the contributions of nitrogen fixation and organic matter were recognized and utilized. But lower cost fertilizers, especially nitrogen, improved genetics, and increased use of herbicides, pesticides, larger machinery, and other technologies led to higher crop yields, increased farm sizes, and specialization. Gradually livestock enterprises became concentrated in areas or regions where row crops were less competitive.

At the same time there was a new era of public interest in agriculture regarding use of chemical fertilizers and pesticides with the focus on food safety. This was heightened by Rachel Carson's *Silent Spring*, which criticized pesticide use and stimulated formation of the Environmental Protection Agency and movement toward organic agriculture and sustainability. Concern continued to increase about "corporate agriculture," how food supplies were affected by industry, and implications for human health and the environment, well beyond soil conservation. Today food and agricultural products are expected to be produced in a sustainable manner that maintains or improves the physical environment, ensures food safety, provides desired taste and nutrition, and provides adequate food and habitat to support biological diversity. Emotions speak loudly, but science is needed to document the factors involved and to drive efforts toward rational and sound solutions.

The CEAP initiative is a critical step to document the science base for conservation programs that are supported by public funds and to plan for the future. Teams of researchers located and assessed the scientific literature on four key conservation practices supported by USDA-NRCS programs. But the effort was also visionary by evaluating scientific gaps and the needs for science in the future. The document will help guide future programs and policies as well as provide insight for the scientific community to focus research on key ecosystem services to serve humanity. Climate change, food safety, water quality, and preservation of biodiversity are only a few of the many factors addressed in the CEAP effort that will affect future policies and management decisions for pastureland and hayland.

The authors are commended for their exhaustive effort and analyses. This CEAP publication is a stake in the ground that should be revisited and revised on a regular basis. Science and public expectations are both dynamic; research on emerging issues needs to be conducted in a timely manner and evaluated for its application on a regular basis. It is imperative that social science and modeling be incorporated into the research agenda to fully understand the holistic process of pasture and hayland management for multiple purposes.

CEAP has been an extraordinary effort focused on a few key USDA-NRCS programs that clearly illustrates the value of science and power of its use. The implications and needs for new knowledge are also valuable to policy makers and to the research and education communities as they move forward.

C. Jerry Nelson  
Editor and Academic Coordinator  
Pastureland and Hayland CEAP Synthesis



The document will help guide future programs and policies as well as provide insight for the scientific community to focus research..."



“

Today food and agricultural products are expected to be produced in a sustainable manner that maintains or improves the physical environment, ensures food safety, provides desired taste and nutrition, and provides adequate food and habitat to support biological diversity.”

# Introduction to the Conservation Outcomes from Pastureland and Hayland Practices

C. Jerry Nelson,<sup>1</sup> Matt A. Sanderson,<sup>2</sup> and Leonard W. Jolley<sup>3</sup>

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The Conservation Effects Assessment Project (CEAP) is a multiagency effort to quantify scientifically the environmental outcomes of conservation practices used by private landowners. It encompasses a national assessment of conservation practices and studies of conservation practices applied to watersheds that are based on detailed syntheses of scientific literature. First, a bibliography of relevant literature was compiled (Maderick et al., 2006). The CEAP grazing lands assessment, begun

in 2006, was partitioned into rangelands, located primarily in the west, and pasture/hayland, located primarily in the east. That was followed by commissioning a synthesis of the scientific literature regarding four conservation practices on pasture and hayland with funding by the U.S. Department of Agriculture–Natural Resources Conservation Service (USDA-NRCS) through the USDA-Agricultural Research Service (USDA-ARS) and the American Forage and Grassland Council

Hay bales waiting to be taken to storage. Photo courtesy of NRCS.





Large capacity mower. Photo by Jerry Cherney.

(AFGC). A similar synthesis was conducted for rangelands (Briske, 2011).

The current CEAP document is the result of a 4-yr effort by pasture, forage, soil, animal, and watershed scientists from across the USA who thoroughly searched, compiled, interpreted, and synthesized the scientific literature regarding its support of production and environmental outcomes from conservation practices on pasture and hayland. A major purpose of CEAP is to expose scientists to needs of practitioners and expectations of policy makers who must account for intended outcomes from each conservation practice.

The overarching goal of this document is to communicate the depth and comprehensiveness of the science that supports each conservation practice on pastureland and hayland in the USA, and to report the areas where the science base is weak or inadequate. This includes answering scientific questions such as:

- Do published scientific studies support how conservation practices affect the

hydrologic cycle on pastureland or hayland?

- What is known about effects of conservation practices on soil quality, plant communities and their dynamics, and air and water quality in major agroecoregions of the USA?
- How can the conservation practices be modified or improved to be more effective?
- What research is needed to gain insight regarding how to evaluate conservation practices at multiple scales, including trade-offs among ecosystem services?

Two workshops were convened to organize the teams of authors and determine the conservation practices on which to focus the literature synthesis. The first workshop held at Louisville, KY in January 2008 included scientists from land-grant universities and USDA-ARS, technical specialists and staff of USDA-NRCS and representatives from the AFGC. The group discussed the most critical conservation issues or practices that should be addressed, defined the boundaries of the synthesis, and proposed potential writing teams. Several conservation practices

ranging from animal trails and walkways (Practice Standard 575) to watering facilities (Practice Standard 614) were considered. In the end, the consensus was that Prescribed Grazing Management (Practice Standard 528), Nutrient Management (Practice Standard 590), Pasture and Hayland Planting (Practice Standard 512), and Forage Harvest Management (Practice Standard 511) should be assessed (<http://www.nrcs.usda.gov/technical/Standards/nhcp.html>; Appendix I). Several other conservation practice standards have relevance to pasture and hayland practices and, where applicable, should be addressed partially within the chapter framework of the most critical practices.

The second workshop, held in Beltsville, MD in May 2008, brought together university scientists, USDA-ARS scientists, and program leaders from the USDA-NRCS, ARS, and the National Institute of Food and Agriculture (NIFA). This group defined the approach and framework with which to document and synthesize the science behind purported production and environmental outcomes of each conservation practice applied to pasture and hayland. A matrix of purposes and criteria for each conservation practice standard and resource concern was developed as the fundamental framework (Table I.1). The matrix was based on a similar model used by the rangeland literature synthesis teams (Briske, 2011).

An introductory chapter discusses pasture and hayland resources of the USA and resource

concerns, which is followed by assessments of the critical conservation practices in separate chapters. The cross-cutting chapter focuses on integrating the results and recommendations of the individual chapters with a look to the future (Chapter 6, this volume).

For each chapter (practice standard) the purported outcomes based on the published purposes and criteria of the conservation practice are treated as testable research questions. Quantitative evidence was assembled and synthesized to test each question or purported outcome. The responsible mechanisms behind the practice are discussed and critical knowledge gaps identified. In essence, each writing team answered the basic questions of 1) does the literature document that the practice accomplishes its goals, 2) if it does, how effectively does it work, 3) if it does not work, why not, and 4) how can the practice be improved?

The synthesis focuses on peer-reviewed literature from the USA; however, in some cases relevant international literature was consulted. In some instances, high-quality research even though not peer reviewed (i.e., gray literature) is used, but only if the report clearly defined the objectives, gave the experimental design, and presented data with quantitative estimates of precision.

Each chapter was prepared by an independent writing team of university and USDA-ARS scientists who were nominated by their peers. An academic coordinator led the editing



This group defined the approach... with which to document and synthesize the science behind purported production and environmental outcomes of each conservation practice...”

**TABLE I.1.** The matrix of conservation practice and resource concerns used to provide structure of the literature synthesis. Outcomes and significance of the assessment were reported in six chapters.

Conservation Practice (chapter, authors)	Resource Concerns					Economic and Social Aspects (Chapter 6, cross cutting, Nelson)
	Soil	Plants	Animals—domestic and wild	Water	Air	
1. Introduction (Sanderson et al.)						
2. Pasture and hay planting (Barker et al.)						
3. Prescribed grazing (Sollenberger et al.)						
4. Forage harvest management (Nelson et al.)						
5. Nutrient management (Wood et al.)						

efforts and kept the teams on task. Each team was supported by USDA-NRCS grazing-land resource specialists from across the USA who provided information, input, and guidance on how USDA-NRCS conservation practice standards are interpreted and applied in the field. Each chapter was peer reviewed by at least two expert scientists external to the writing team. They were also reviewed by two–four NRCS specialists.

Parts of individual chapters were presented at symposia held in conjunction with the annual meetings of the American Forage and Grassland Council (AFGC) in June 2009, the Crop Science Society of America (CSSA) in November 2009, and at the Fourth National Conference on Grazing Lands (GLCI) in December 2009 (Briske et al., 2010). A summary poster of salient findings and recommendations was presented at the annual conference of the AFGC in June 2010. Summations of the findings and implications

were presented at the annual meetings of the AFGC in June 2011, and the Soil and Water Conservation Society in July 2011.

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Round bales of grass hay in Ohio. NRCS photo by Rob Rhyan.



# Executive Summary: New Foundations for Conservation Standards<sup>1</sup>



C. Jerry Nelson, David J. Barker, Lynn E. Sollenberger, and C. Wesley Wood

## THE CEAP INITIATIVE

Forage, grasslands, and grazing lands constitute more than two-thirds of agricultural land in the USA, where they contribute to food production and provide several ecosystem goods and services. Increasing and sustaining provision of these goods (e.g., wildlife and aesthetics) and services (e.g., conserving and protecting soil, water, and air resources) usually requires public funding and makes government agencies responsible and accountable for the investments. The Conservation Effects Assessment Project (CEAP) is a multiagency effort begun in 2003 to evaluate published research to determine if outcomes desired from conservation practices used by private landowners are supported by science. Results from CEAP will help policy makers and program managers implement existing conservation programs and design new ones to meet national goals more effectively and efficiently. In addition, CEAP identified gaps in scientific knowledge and recommended ways to build a timely science base for meeting simultaneous goals of production and conservation, and providing other ecosystem services expected by the public.

Previous CEAP assessments focused on cropland, wetlands, and wildlife. The grazing lands assessment was partitioned into rangelands, located primarily in the west, and pasture/hayland, located primarily in the east. For the pasture/hayland effort, teams of prominent scientists with expertise related to four selected conservation standards were formed in 2008 to search thoroughly, compile, interpret, and synthesize the scientific literature regarding its support of production and environmental outcomes. Natural Resources Conservation Service (NRCS) advisory personnel were associated with each team to clarify practical aspects of describing, designing, and installing the practice. Dr C. Jerry Nelson served as Academic Coordinator of the project and editor of the publication. The procedure was similar to that used by literature

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Results...will help  
policy makers  
and program  
managers  
implement  
existing  
conservation  
programs and  
design new ones  
to meet national  
goals”

<sup>1</sup>Excerpt from Nelson, C.J. (ed.) 2012. *Conservation Outcomes from Pasture and Hayland Practices: Assessment, Recommendations and Knowledge Gaps*. Allen Press, Lawrence, KS.



“

This effort now provides a solid framework for evaluating the current situation, and for focusing, designing, implementing, and justifying future iterations”

synthesis teams for the rangeland CEAP assessment (Briske, D.D. [ed.] 2011. Conservation benefits of rangeland practices: Assessment, recommendations, and knowledge gaps. Allen Press, Lawrence, KS.)

The book contains an introduction, four chapters of in-depth assessment of a specific practice, and another chapter on synthesis and perspectives. Chapters on practice standards include:

- Planting for Hay, Silage, and Biomass (Code 512, 2010 edition)
- Prescribed Grazing (Code 528, 2007 edition)
- Forage Harvest Management (Code 511, 2008 edition)
- Nutrient Management (Code 590, 2006 edition)

Each writing team answered the basic questions of 1) does the literature document that the practice accomplishes its goals; 2) if so, how effectively does it work; 3) if not, why not; and 4) how can the practice be improved? Areas needing some or additional research were pointed out. Each chapter was reviewed by the academic coordinator and U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS) liaison to ensure the review was comprehensive and had addressed the purposes and criteria. Revisions were reviewed by the academic coordinator, two peer experts not related to the CEAP effort, and by at least two NRCS practitioners. In each case the authors addressed all issues raised by reviewers.

The search, review, and evaluations were rigorous, thorough, and comprehensive, going well beyond any previous assessments of pasture and hayland practices for conservation purposes. This effort now provides a solid framework for evaluating the current situation, and for focusing, designing, implementing, and justifying future iterations and assessments of conservation practice standards for pastures and haylands. This Executive Summary highlights overarching assessments and recommendations by the writing teams. These assessments

are supported by detailed analyses recorded in the book chapters and summarized in tables published within the Executive Summary.

## CURRENT STATUS OF SCIENTIFIC KNOWLEDGE

Agriculture in the USA is continuing to change rapidly from nature-integrated, family-centered operations to dominance of large-scale operations using a corporate or industrial model. Farm size, machinery size, and land prices are increasingly based on crop production that depends on industrial inputs ranging from cultivars to chemicals. Gradually, natural grasslands, hay fields, and woodlands have been converted to large-scale monoculture crop production in large fields, which has displaced desirable habitat for wildlife and reduced plant biodiversity that provide natural abatement of potential risks to the environment. Credibility of agriculture is being questioned, because the general public often identifies large-scale, corporate farms with a business interested mainly in profit, having only a marginal interest in ecosystems, and increasing use of nonfamily employees who may be exploited.

### Research Needs Are Broader in Context

Current and future research for pastures and hay fields needs to be broader in scope, more complex, more interdisciplinary, and longer term. Experimental methods, focused largely on a specific hypothesis with rigorous protocols to ensure appropriate measurements for 2–4 yr, are used to answer input–output questions. In contrast, conservation questions, especially with pastures and haylands, involve nature and natural settings, usually have several animal and plant variables, allow less experimental control, and must be conducted for longer time periods, in many cases for 10 or more years. Change toward the ecological equilibrium of a pasture treatment or among perennial forages in mixtures takes time before that endpoint, the key objective, can be evaluated. Cooperation with ecologists and social scientists is needed to research these multiple outputs to answer complex management questions for pastures and haylands.

### Expectations of Agriculture Go Beyond Food Supply

Food supply has traditionally been the major expectation from agriculture, but that food must also be safe, healthy, and have a desired taste. Public interest and pressure includes recognizing animal rights, managing livestock waste, improving water quality of streams and lakes, and conserving soil and biodiversity. Although acceptance and use of biotechnology and genetic engineering of crops by U.S. farmers and consumers occurred rapidly, demand for organic products also increased, especially among high-income families. Some prefer “natural” foods that are different from organic foods and are labeled “locally produced,” “grass-fed,” “hormone-free,” or “free-range,” for example, or have other value-added traits. New research will require cooperation with social scientists so human elements of both consumers and producers receive appropriate attention and understanding as changes occur.

These concerns also point toward greater use of hayland and animal manures in crop rotations and use of more pastureland for meat and milk production.

### Private Industry Brings Mixed Reactions/Emotions

Amalgamation or connectivity among agricultural industries has brought new technologies that are adopted rapidly by crop farmers, giving the public perception of industrial control of agriculture. The private sector greatly influences machinery, cultivars, chemical fertilizers, pesticides, and other technologies now used routinely in “conventional” agriculture. Research by private industry and patenting, including genetic engineering, have allowed private plant breeders to develop new cultivars with improved water-use efficiency, nutrient-use efficiency, herbicide tolerance, and disease and insect resistance of major crop plants. These methods and materials are usually adopted quickly, with the outcome being greater economic competitiveness of grain and row crops, higher land prices, and fewer rotations with forages and use of animal manures.

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future research...  
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and longer term.”





Local knowledge about climates, soils, plant species, and livestock needs is essential to provide credible guidance”

### Public Support Is Needed for Pasture- and Hayland Issues

Conservation of natural resources will continue to be a national priority with additional state support. There are few technologies being developed by the private sector for forages aside from some seed supplies; seeding, harvest, and packaging machinery; fertilizers; and a few pesticides. Even so, significant management technologies such as rotational stocking, nutrient management, harvest management, and no-till seeding have emerged from public-sector research to improve yield and quality of pastures and hay fields while conserving resources. Private industry contributes machinery that helps implement conservation practices, but does little in areas where there is low or minimal potential for profit on their investment. Thus, enhanced public support will be needed for research, education, and incentives for volunteer adoption of needed practices.

### A New Era Is Emerging for Pasture and Hayland

Forages are renowned for their capacity to reduce erosion, protect surface waters, provide low-cost feed, benefit crop rotations, support biodiversity, and provide sites to receive animal manures. There are hundreds of grass, legume, and forb species used for pasture and harvested forage. Each species has its own growth form, response to biotic and abiotic stresses, and conservation value. Pastures and forages provide good potential for erosion control on sloping and lower productivity sites, and are quality materials for riparian areas and waterways that reduce risks of plant nutrients, livestock wastes, and antibiotics as runoff pollutants. These diverse species support food chains and quality habitats for wildlife. Although the challenges are great, pastures and haylands can be managed to provide economic uses of these landscape positions while providing many ecosystem services that are valued by the public.

### Summary

It is impossible to research the multiplicity of combinations of problems and potential solutions over the range of sites needing conservation practices. Thus, dependence is on basic research knowledge that is augmented by experience of the agency personnel at the local level. Local knowledge about climates, soils, plant species, and livestock needs is essential to provide credible guidance for implementation of the best practice, its maintenance, and its long-term effectiveness. Education of landowners is also critical for understanding the goals and ways adaptive management is used to maintain the area so it provides the greatest function. Modeling will help understand interactions among the biological, economic, social, and cultural expectations.

### SUMMARY OF FINDINGS BY CONSERVATION PRACTICE

Each team evaluated the current level of research support for each purpose and its underlying criteria. Collectively, the team reached consensus and developed the suggestions reported in the individual chapters in the published book. The lead authors then gleaned these major findings from the chapters, integrated the assessments, and developed the tables and Executive Summary.



Site- and species-specific management during the first year is critical;”

### PLANTING FOR HAY, SILAGE AND BIOMASS CHAPTER 2

This USDA–Natural Resources Conservation Service (NCRS) practice focuses on establishing adapted and/or compatible species, varieties, or cultivars of herbaceous species suitable for pasture, hay, or biomass production. Purposes include the following:

- Improve or maintain livestock nutrition and/or health
- Provide or increase forage supply during periods of low forage production
- Reduce soil erosion
- Improve soil and water quality
- Produce feedstock for biofuel or energy production

**Key Synthesis Findings (from Table ES.1)**

- Publications covered 162 grass, legume, and forb species, but more than 50% were on only 28 species. Research is needed on more species for specialized situations such as unknown dormancy conditions or unique establishment requirements.
- Adaptation to a wide range of conditions exists to provide species and management options for specific locations.
- Establishment is improved by using legume seed inoculated with the proper strain of rhizobia. Strains for some species differ in effectiveness, but may not be available. Rhizobia are not available commercially for less-common legume species.
- The best measure of seed quality is the germination test (percentage and date). Seed size and storage conditions are also important, but are not reported commercially.
- Phosphorus applications gave more consistent improvement in grassland establishment than did potassium or nitrogen. Specific responses depend on plant species, other nutrients, and competition from nonsown species. Recommendations for seeding-year stands differ from those for mature stands.
- Satisfactory establishment results from many methods of site preparation, planting methods, and species, typically with a direct relationship between cost and success. Best advice is from local specialists who adapt research to local conditions. Greater use of modeling may be warranted.
- Planting success depends on a period of favorable temperature and rainfall. Timely weather forecasting is advantageous.
- There is no benefit from sowing rates higher than those recommended by state agencies. Seeding rate should be adjusted to deliver seed on a pure-live-seed (PLS) basis.
- Seeding depth is critical; small seeds should be planted near the soil surface with adequate soil coverage. A general guide is to plant a seed no deeper than seven times its diameter.
- Site- and species-specific management during the first year is critical; species such as native warm-season grasses take more than 1 yr to be ready for their intended use. Seedling root growth is critical.
- Establishment is greatly improved by control of weeds or existing vegetation, but data were inconsistent as to the best method. Risk of runoff and soil erosion is greatest when there is little vegetation, and is extended with species that take more time to become established.
- There was little research on effects of establishment time or methods on water quality, soil erosion, gaseous emissions such as CO<sub>2</sub> or NO<sub>x</sub>, other environmental factors, and food sources and habitat for wildlife.
- Few research studies consider establishment of biomass species other than those, such as switchgrass, that also can be forage or pasture crops.



Recognizing and using adaptive management like weed control, fertilization, and cutting times will assist managers”



**Implications:** Generalized descriptions for forage and biomass planting are nearly impossible because of the almost infinite number of combinations of species, cultivars, planting methods, planting times, fertilizer regimes, seed coatings and treatments, climatic conditions, and final uses for the stand. Specifications to use local guidelines and expertise are warranted, because many of those guidelines have been researched locally. New species and new developments in cultivars, seed coating, fertilizer products, options for weed and pest control, and potentials for genetically modified forage and pasture plants suggest an ongoing need for continued research on establishment practices in each major climatic zone of the USA.

Establishment of forages for biomass harvesting, wildlife, erosion control, and water harvesting requires additional research, hopefully conducted with teams of ecologists and social scientists that support modeling to strengthen understanding relationships and transferability of information. Research is needed to determine when or at what stage plants are deemed to be established, and to quantify effects of establishment methods on runoff and erosion, wildlife food supplies, and time when the planting is ready for its intended use.

Research is needed on establishment on lower productivity and sloping soils that are often used for forage supplies and ecological benefits. Education of agency staff will help blend experience and science for planning and implementing the practice. Recognizing and using adaptive management like weed control, fertilization, and cutting times will assist managers correct emerging situations to minimize risk, ensure rapid and successful establishment, and provide maximum conservation benefit. This will require educational programs for managers focused on desired outcomes including forage supplies and other ecosystem services.

**TABLE ES.1.** Summary of purposes, criteria used for evaluation, and level of research support of Natural Resources Conservation Service Conservation Practice Standard for Forage and Biomass Planting, Code 512.

Purposes of the practice standard	Criteria used for assessing achievement of purpose	Support by research based on 350 scientific publications and 162 different species
Improve or maintain livestock nutrition and health	by establishing species and cultivars with greater production, and potential to increase animal intake	Species and cultivars differ in production and quality. But increased livestock production was assumed more likely from increased stocking rate than intake per head.
	by establishing species and cultivars with greater nutritive value (i.e., energy content, protein or mineral concentration)	A negative relationship often occurs between production and nutritive value. Less-productive species and cultivars (above) can have higher nutritive value.
	by replacing species with low nutritive value or with high levels of toxic compounds	Whether through complete stand replacement (e.g., full cultivation) or partial stand replacement (e.g., sod or no-till seeding), species with greater nutritive value can be introduced into grasslands.
	by establishing species and cultivars to provide nutrition during periods of feed deficit (e.g., extend forage production season)	Species and cultivars that are tolerant to cold can improve early-spring and late-autumn production, and those tolerant to heat and drought can improve summer production. Major species are characterized.
	by establishing species with wildlife benefits such as nesting habitat, cover, biodiversity, and insects	Wildlife species vary in nutritional and habitat requirements that cannot be met by any single forage species. Species-rich vegetation offers more benefits to wildlife than monocultures.

TABLE ES.1. continued.

Purposes of the practice standard	Criteria used for assessing achievement of purpose	Support by research based on 350 scientific publications and 162 different species
Provide or increase forage supply during periods of low forage production	by establishing species and cultivars with greater production potential	More productive species and cultivars can be harvested for hay or silage, for use during periods of low forage production.
	by establishing species with higher environmental tolerance (e.g., cold, heat, drought, pH, salinity)	Cold- and drought-tolerant species with greater forage production during feed-deficit periods can provide in situ grazing and reduce hay or silage feeding costs.
	by establishing annual forage crops to fill predicted feed deficits for harvest or grazing	Annual forage species can be planted into existing grassland, or as cover crops in grain systems, to provide forage for in situ grazing or for hay or silage harvest.
Reduce soil erosion	by establishing perennial species that provide year-round ground cover, and by avoiding cultivation	Perennial grasslands have year-round soil cover with lower rates of soil loss than bare soil and can be managed for improved persistence.
	by establishing species with improved adaptation and greater persistence	Stand longevity of new alfalfa cultivars with multiple insect and disease resistance may be more than double that of older cultivars.
	by using no-till methods for establishment to alleviate soil cultivation	Sod- and no-till seeding, especially with herbicide use for vegetation control, can successfully establish grasslands.
	by establishing plants with greater ground cover that reduces the rate of surface water flow	Plants with greater ground cover and denser vegetation have less runoff and higher water infiltration. Vegetation density is also affected by management.
Improve soil and water quality	by establishing species with vigorous root growth that ensures carbon sequestration and nutrient uptake	In general, grasses have dense, fibrous root systems, whereas legume root systems may include large taproots and crowns; rooting characteristics are affected by management as well as establishment practices.
	by establishing N-fixing legumes, thus reducing the need for fertilizer N	Legumes are relatively fast to establish, can be included in grassland mixtures, or can be no-till drilled (sod seeded) or broadcast seeded (frost seeded) into grass stands
	by establishing species that ensure efficient nutrient cycling, and support active populations of soil macro- and micro-organisms	Nutrient cycling and some soil microbial processes are impaired during establishment, but resume once the stand is established. Later on, nutrient cycling is affected significantly by forage removal as hay or silage.
	by reducing soil erosion	Where water quality is a critical issue, new seedlings should use no-till methods or fast-establishing companion crops to avoid bare soil or reduce time of bare soil exposure.
Produce feedstock for biofuel or energy production	by establishing species and cultivars with high biomass potential	The most productive biofuel feedstocks (miscanthus and giant reed) can be established vegetatively with stems and/or rhizomes. Switchgrass can be established from seed.
	by establishing species and cultivars with unique characteristics for biofuel or energy production (e.g., low ash, high cellulose)	Species differ in concentration and types of structural and nonstructural carbohydrates for biofuel purposes. Several forage species have high ash content and may be less suitable for biofuel purposes than others.



Grazing intensity...is the most important grazing strategy on pasturelands;”

## PREScribed GRAZING CHAPTER 3

This USDA-NRCS practice standard focuses on managing harvest of vegetation with grazing and/or browsing animals. The practice may be applied as a part of a conservation management system to achieve one or more of the following purposes:

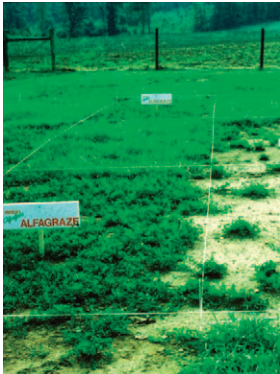
- Improve or maintain desired species composition and vigor of plant communities
- Improve or maintain quantity and quality of forage for grazing and browsing animals’ health and productivity
- Improve or maintain surface and/or subsurface water quality and quantity
- Improve or maintain riparian and watershed function
- Reduce accelerated soil erosion, and maintain or improve soil condition
- Improve or maintain the quantity and quality of food and/or cover available for wildlife
- Manage fine fuel loads to achieve desired conditions. Note: It was decided to not address this purpose, as it is covered in detail by the Rangeland CEAP assessment (D. D. Briske, 2011)

### Key Synthesis Findings (from Table ES.2)

- Grazing practices have major influence on plant, livestock, water, soil, and wildlife.
- Grazing intensity (i.e., stocking rate or plant height) is the most important grazing strategy on pasturelands; and conservation plans should prioritize proper grazing intensity.
- Stocking method is useful for fine-tuning the system once appropriate grazing intensity is imposed. Rotational vs. continuous stocking positively affects forage accumulation and utilization as well as important measures of water quality.
- Adequate forage ground cover reduces runoff and improves water infiltration, wildlife habitat, avian nesting sites, and food supply for wildlife and livestock.
- Cograzing or grazing by one livestock species vs. another can be used to manipulate botanical composition of pastures, decrease abundance of unwanted plants, and create greater patchiness in plant height that improves wildlife habitat.
- Time scales for most pastureland research have been limited such that long-term changes in plant persistence, livestock diets, and effects on soil, water, and wildlife may be inadequately described.

**Implications:** Grazing intensity is the prescribed grazing strategy having greatest impact on plant, animal, soil, water, and wildlife. Thus, defining and achieving an optimal grazing intensity should be of highest priority in conservation planning and implementation. Although societal interest and emphasis on soil, water, and wildlife is increasing, there is a paucity of literature addressing effects of prescribed grazing on these ecosystem components. Future grazing studies on pastureland should be more comprehensive in scope, including these components in addition to plant and livestock measures, and be carried out over longer time periods to allow the full effects of prescribed grazing to be quantified. These data will provide the basis for development of effective pastureland ecosystem models.

A significant weakness of existing literature is the lack of consistent or standardized research protocols for measuring forage mass, accumulation, nutritive value, and species composition, especially in comparisons among stocking methods. There appears to be a significant future role for emphases including 1) use of prescribed grazing in adaptive management to correct undesirable trends in pastureland response and restore desired grassland condition; 2) better education of end users regarding implementation of prescribed grazing technology; 3) detailed monitoring and reporting of the impacts of implementation of prescribed grazing practices to use adaptive management more effectively to adjust the system to meet goals. Accumulation of monitoring data will also assist in future designs and education programs for landowners.



**TABLE ES.2.** Summary of purposes, criteria used for evaluation, and level of research support for Natural Resources Conservation Service Conservation Practice Standard for Prescribed Grazing, Code 528. Each criterion is evaluated for degree of research support from studies using five different grazing strategies.

Purposes of the practice standard	Criteria used for assessing achievement of the purpose	Support by research for each criterion (level of support in parentheses) <sup>1</sup>
Improve or maintain desired species composition and vigor of plant communities	by providing grazed plants sufficient recovery time to meet objectives	Stocking method (SS); season of grazing (SS)
	by improving or maintaining vigor of plant communities, especially key species	Grazing intensity (SS); stocking method (MS); season of grazing (MS); type and class of livestock (MS)
	by enhancing diversity of plants and optimizing delivery of nutrients to animals	Grazing intensity (SS); stocking method (WS); distribution of livestock (MS)
	by combining it with other pest management practices, which can promote community resistance to invasive weed species and enhance desired species	Grazing intensity (SS); stocking method (MS); season of grazing (MS)
Improve or maintain quantity and quality of forage for grazing and browsing animals' health and productivity	by reducing animal stress and death from toxic or poisonous plants	None documented
	by improving and maintaining plant health and productivity	Grazing intensity (SS); stocking method (MS); season of grazing (SS); type and class of livestock (MS)
	by basing management on target levels of forage utilization or stubble height as a tool to help ensure goals are met	Grazing intensity (SS)
	by locating of feeding, watering, and handling facilities to improve animal distribution	Distribution of livestock in the landscape (MS)
Improve or maintain surface and/or subsurface water quality and quantity, and riparian and watershed function	by improving or maintaining riparian and watershed function	Grazing intensity (SS); stocking method (MS); season of grazing (SS); distribution of livestock (MS)
	by minimizing deposition or flow of animal wastes into water bodies	Grazing intensity (SS); stocking method (WS); season of grazing (WS); distribution of livestock (SS)
	by minimizing animal effects on stream bank stability	Grazing intensity (WS); stocking method (MS); season of grazing (MS); distribution of livestock (SS)
	by providing adequate litter, ground cover, and plant density to maintain or improve infiltration capacity of the vegetation	Grazing intensity (SS); stocking method (MS); season of grazing (MS)
	by providing ground cover and plant density to maintain or improve filtering capacity of the vegetation	Grazing intensity (SS); stocking method (MS); season of grazing (MS)
	by minimizing concentrated livestock areas, trailing, and trampling to reduce soil compaction, excess runoff, and erosion	Grazing intensity (SS); stocking method (MS); season of grazing (MS)

TABLE ES.2. continued.

Purposes of the practice standard	Criteria used for assessing achievement of the purpose	Support by research for each criterion (level of support in parentheses) <sup>1</sup>
Reduce accelerated soil erosion, and maintain or improve soil condition	by reducing accelerated soil erosion	Grazing intensity (MS)
	by minimizing concentrated livestock areas to enhance nutrient distribution and improve ground cover	Grazing intensity (MS); stocking method (MS)
	by improving carbon sequestration in biomass and soils	Grazing intensity (MS)
	by application of soil nutrients according to soil test to improve or maintain plant vigor	Grazing intensity (MS)
Improve or maintain the quantity and quality of food and/or cover available for wildlife	by maintaining adequate riparian community structure and function to sustain associated riparian, wetland, flood plain, and stream species	Grazing intensity (SS); season of grazing (SS); distribution of livestock (MS)
	by providing for development and maintenance of the plant structure, density, and diversity needed for desired fish and wildlife species	Grazing intensity (SS); season of grazing (SS); type and class of livestock (MS); distribution of livestock (MS)
	by improving the use of the land for wildlife and recreation	Grazing intensity (SS); season of grazing (MS); distribution of livestock (MS)
	by avoiding any adverse effects on endangered, threatened, and candidate species and their habitats	Grazing intensity (MS); season of grazing (MS); distribution of livestock (MS)

<sup>1</sup>The five grazing strategies were grazing intensity, stocking method, season and deferment of grazing, type and class of livestock, and distribution of livestock in the landscape. SS = strongly supported; MS = moderately supported; VVS = weakly supported; for grazing strategies not shown there was no support in the literature that this strategy affected the criterion in question.





## FORAGE HARVEST MANAGEMENT CHAPTER 4

This USDA-NRCS practice standard focuses on timely cutting and removal of forages from the field as hay, green chop, or ensilage. The practice applies to all land uses where machine-harvested forage crops are grown. Purposes include the following:

- Optimize yield and quality of forage at the desired levels
- Promote vigorous plant regrowth
- Maintain stand life
- Manage for the desired species composition
- Use forage plant biomass as a soil nutrient uptake tool
- Control insects, diseases, and weeds
- Maintain and/or improve wildlife habitat

### Key Synthesis Findings (from Table ES.3)

- Most research was on management with outputs of yield and forage quality. Only a few long-term studies evaluated effects on persistence or botanical composition.
- The State Agricultural Research System provides local research on cutting height and frequency for yield and quality of major forage species, generally when grown in monoculture.
- Adaptation of major species and their use characteristics have been researched at local levels.
- Ecosystem research has been focused on quantifying N and P losses from the field with implications for efficiency of nutrient use and improved water quality.
- Integrated pest management has emphasis on alfalfa insects and a few others like army worm. Most diseases are addressed with the use of genetic resistance. Biocontrol has been researched for a few insects and weed species with moderate success.
- Delaying first harvest of hay or hay-crop silage of many cool-season species favors success of ground-nesting birds; cutting 100 mm above soil level improves survival of turtles.



Only a few long-term studies evaluated effects on persistence or botanical composition.”



Periodic monitoring of the practice and education of land managers will help understand challenges”

- Several warm-season native perennials are lauded for wildlife benefits because of growth habit, maturity, and provision of protection over the winter, but few research studies have quantified the superiority over other species.
- Allowing growth during fall improves overwintering success in northern environments.
- Growth habits of cool-season grasses in spring favor harvest for hay compared with summer when leaf growth favors grazing or accumulating forage for winter grazing.
- Legumes fix nitrogen for hayland that can be carried over for crop production.
- Principles for making and storing quality hay, haylage, and silage are well documented.
- Harvest and storage losses are well characterized for both hay crops and silages; strategies to minimize losses have been researched for most conditions.

**Implications:** Agricultural Experiment Stations have developed sound management practices for major species that are transferable among states. Managing for forage yield and quality is well known for major species, with less information available on stand longevity. There is growing awareness that wheel traffic damages plants and causes soil compaction, reducing production and persistence, especially for legumes, and may increase runoff. Similarly, key soil criteria, weather data, and life cycles of biota need to be incorporated into the research design, measurements taken, and interpretation of data to elucidate major interactions in such complex systems.

Long-term research on pure stands and mixtures is needed to understand changes among component plant species and other biota over time. Further, interactions with forage management suggest one wildlife form may be enhanced at the detriment of another form. Specific wildlife types need to be evaluated to understand effects of field sizes, forage species, position on the landscape, and management practices on success of birds, small mammals, and other wildlife. Entomologists, plant pathologists, soil scientists, wildlife specialists, and ecologists need inputs to scale the research so results can be fitted into models for comprehensive ecosystem assessments. Periodic monitoring of the practice and education of land managers will help understand challenges, promote use of adaptive management to mitigate problems, and evaluate attempts to restore or maintain the practice for the stated goal.



**TABLE ES.3.** Summary of purposes, criteria used for evaluation, and level of research support of Natural Resources Conservation Service Conservation Practice Standard for Forage Harvest Management, Code 511.

Purpose of the practice standard	Criteria used for assessing achievement of the purpose	Support by research
<b>Optimize yield and quality of forage at the desired levels</b>	harvest at frequency and height to maintain healthy plant community as recommended by state extension service	Strong support on major species, limited on other species being used in special situations.
	harvest forage at stage of maturity for desired quality and quantity	Strong support on major species to optimize yield and quality.
	delay harvest if prolonged or heavy precipitation is forecast that would damage the cut forage	Moderate, need comparative data on rate of yield and quality change due to weather or later maturity.
	harvest silage/haylage crops within the optimum moisture range for the storage structure(s) being utilized	Strong support for haylage and silage crops over a range of moisture contents.
	use state extension service recommendations for optimum moisture content and how to determine moisture content	Strong support for optimum content, but comparison of methods for measurement needs research.
	treat direct-cut hay crop silage (moisture content > 70%) with chemical preservatives or add dry feedstuffs	Generally supported, research is variable on consistency of results achieved. Cost-effectiveness needs more research.
	invert swaths when moisture content is above 40% and rake hay at 30–40% moisture to maintain hay quality	Inverting assists the drying process, but leaf loss on some species can be high. Need research on different methods and cost effectiveness.
	bale field-cured hay at 15–20% moisture; bale at 20–35% moisture if it is to be dried by forced air	Strong support, but need more research on quality losses from field drying vs. costs for water transport and energy costs for forced-air drying.
	chop ensilage to a size appropriate for the storage structure that allows adequate packing	Strong support
<b>Promote vigorous plant regrowth</b>	cut plants at a stage or interval that provides adequate food reserves and/or basal axillary tillers or buds for regrowth or reproduction without loss of plant vigor	Strongly supported for upright perennial legumes and grasses. Moderate support for prostrate species that use leaf area to provide the major energy source.
	cut plants at a height that promotes vigor and health of the desired species	Strong support for low cutting of alfalfa for yield, but not for soil erosion and some wildlife.
<b>Manage for desired species composition</b>	harvest at the proper height and frequency to maintain desired species composition	Strong support on how height and frequency can affect species in the short term which would be useful as an adaptive management method.
	fertilize with appropriate minerals at the correct time in the growing season	Strong support for use of N, P, and K and time during the season to alter the botanical composition.

TABLE ES.3. continued.

Purpose of the practice standard	Criteria used for assessing achievement of the purpose	Support by research
Use forage plant biomass as a soil nutrient uptake tool	use a harvest regime that utilizes the maximum amount of available or targeted nutrients	Moderate research on use of forage plants to utilize excess nutrients in cropping systems
	when desired, select species that can maximize nutrient uptake	Variation in nutrient uptake among species is known, but balance is more critical than uptake of a single nutrient.
	use proper balance of nutrients such as nitrogen to avoid toxic plant material for animals	Strong research support on NO <sub>3</sub> and HCN challenges in grasses. Some research on N on alkaloids in some cool-season grasses.
Control insects, diseases and weeds	select harvest periods to control disease, insect, and weed infestations	Weak research support except for insects on alfalfa (weevils, potato leafhoppers).
	evaluate pest management options by planning conservation practice standard Pest Management (595)	Strong integrated pest management (IPM) research for alfalfa insects, but weak for other species, need more research.
	lessen incidence of disease, insect damage, and weed infestation by managing for desirable plant vigor	Strong support for maintaining plant vigor and competition to reduce challenges
Maintain or improve wildlife habitat	if suitable habitat for wildlife species is desired, appropriate harvest schedules(s), cover patterns, and plant height should be maintained to provide suitable habitat	Some support for delayed harvest of first cut for ground nesters and leaving stubble for winter cover and food source; raise cut height for turtles.
	avoid harvest and other disturbances during nesting, fawning, and other critical times	Some research indicates biomass crops will be harvested late and will provide habitat in summer and winter for some forms of wildlife.



Most purposes were supported moderately to strongly by the U.S. scientific literature.”

## NUTRIENT MANAGEMENT CHAPTER 5

This USDA-NRCS practice standard focuses on managing the amount, source, placement, form, and timing of applications of plant nutrients and soil amendments. The practice applies to all lands where plant nutrients and soil amendments are applied. Purposes include the following:

- To budget and supply nutrients for plant production
- To utilize manure or organic byproducts as a plant nutrient source properly
- To minimize agricultural non-point-source pollution of surface and ground water resources
- To protect air quality by reducing nitrogen emissions (ammonia and NO<sub>x</sub> compounds) and the formation of atmospheric particulates
- To maintain or improve the physical, chemical, and biological condition of soil

### Key Synthesis Findings (from Table ES. 4)

- Most purposes were supported moderately to strongly by the U.S. scientific literature.
- Several emerging areas of nutrient management require further research and development to ensure sustained and environmentally conscious pasture and hayland production.
- Major concerns with manure or organic by-products are 1) uncertainty regarding phytoavailability of nutrients contained and 2) economic evaluations.
- Simulation models, coupled with rapid determination of pools and rates of mineralizable N and P, and phytoavailable K in organic nutrient sources, could be powerful decision support tools to help optimize nutrient management in systems.

- There are few data on costs, benefits, and cost effectiveness of available best management practices for retarding nutrient loss from pastures and haylands.
- A national P index is needed to predict losses of runoff P over a wide range of conditions.
- A national nitrate leaching index is needed that will accurately predict nitrate leaching losses over a wide range of conditions.
- Improved existing and new process models are needed to predict nutrient losses from divergent nutrient loadings, soil properties, and climatic conditions.
- Literature is scarce on reducing N emissions and formation of atmospheric particulates. Most U.S. research has been in the southeast; more is needed from other regions to fully evaluate effects of management on air quality.
- Less than 5% of N applied to U.S. pastures is lost to the atmosphere as gaseous N.
- Gaseous-N loss increases with increasing rates of applied N; losses are greater from organic-N sources than from inorganic-N sources.
- Pasture and hayland fertilization maintains or moderately improves soil organic matter concentration over the long term.
- Overapplication of N and P to pastures and haylands results in their buildup and may promote escape to surface and ground waters, and N escape to the atmosphere.
- Salt buildup in soils due to fertilization of pastures and haylands is typically of no consequence at current soil concentrations.
- Heavy metals accumulate in U.S. pasture and hayland soils where animal manures are applied, but at current soil levels do not influence pasture and hayland productivity.
- Long-term manure applications have a slight liming effect on pasture and hayland soils.
- No U.S. research was found relating soil physical properties to nutrient management of pastures or haylands.
- Current data are insufficient to interpret effects of nutrient cycling on pastures and interactions with grazing management and pasture fertilization.

“

A national P index is needed to predict losses of runoff P over a wide range of conditions.”

**Implications:** Most research is focused on plant productivity, usually of short duration, leaving a strong need for long-term research regarding impacts of nutrient management on soil, water, and air quality. This need is particularly evident for pastures and haylands where manures and other organic by-products are used as nutrient sources. Basic information and quick-test methods for nutrient release from organic nutrient sources need to be developed and standardized



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Code 590 should be separated into one focused on traditional crops, mainly annuals, and one focused on pastures and hayland.”

for use across the USA. Simulation models coupled with appropriate methods for rapid determination of pools and rates of mineralizable N and P, and phytoavailable K from organic nutrient sources, could provide powerful decision-support tools to optimize nutrient management. Phosphorus and N are the most common nutrient-related water pollutants.

A national P-index and a nitrate leaching index would help planning by predicting runoff-P losses and nitrate leaching, respectively, over a wide range of conditions. Moreover, improvement of existing and development of new process models could predict nutrient losses from divergent nutrient loadings, forage or pasture species, soil properties, and climatic conditions. Once nutrient losses are defined the appropriate management practice can be implemented and impacts on other ecosystem services can be determined.

Lastly, the practice standard revised in 2011 covers some of these issues and is an improvement. But the wide difference in management practices and expected outcomes strongly indicates that Code 590 should be separated into one focused on traditional crops, mainly annuals, and one focused on pastures and hayland. This would allow more specific coverage of nutrient management during establishment and maintenance of long-term stands for production, forage quality, persistence, and provision of ecosystem services. The focus on pastures should consider stocking rates and grazing methods that affect nutrient cycling and times available for nutrient applications. The focused practice standard could emphasize perennial crops grown on lower-productivity sites that have more risk of runoff, yet have more potential for wildlife and other ecosystem benefits. The code should include riparian areas and waterways and other critical sites where forages play major roles.

**TABLE ES.4.** Summary of purposes, criteria used for evaluation, and level of research support for Natural Resources Conservation Service Conservation Practice Standard for Nutrient Management, Code 590.

Purposes of the practice standard	Criteria for assessing achievement of the purpose	Support by the literature
Budget and supply nutrients for plant production	by developing a nutrient management budget using all potential sources of nutrients, including crop residues, legume credits, and irrigation water	Strong support for hayland, but need manure credits for pastures and research on phytoavailability.
	by establishing realistic yield goals based on soil productivity information, historical yield data, climate, management, and local research	Moderate support, more research needed on lower quality land sites.
	by specifying the source, amount, timing, and method of applying nutrients to each yield goal while minimizing movement of nutrients and other potential contaminants to surface or ground waters	Strong support for application ahead of growth, more research needed for offseason applications.
	by restricting direct application of nutrients to established minimum setbacks (e.g., sinkholes, wells, gullies, surface inlets, or rapidly permeable soil areas)	Strong support, but mainly based intuitively from other studies. More research needed for pastures and haylands.
	address the amount of nutrients lost to erosion, runoff, drainage, and irrigation	Strong support that this is critical, but need more soils and sites, perhaps models.
	applications be based on current soil (within 5 yr) and tissue test results according to land grant university guidance	Moderate support, current soil tests do not report P or N indices.

TABLE ES.4. continued.

Purposes of the practice standard	Criteria for assessing achievement of the purpose	Support by the literature
<b>Properly utilize manure or organic by-products as a plant nutrient source.</b>	by reducing animal stress and death from toxic or poisonous plants	Moderate support, but not a major problem in humid areas.
	by improving and maintaining plant health and productivity	Strong support, except on roles of organic by-products.
	by basing management on target levels of forage utilization or stubble height as a tool to help ensure goals are met	Moderate support showing principles; little on specific management practices.
	by locating of feeding, watering, and handling facilities to improve animal distribution	Strong support that would benefit from quantitative models to better define.
<b>Minimize agricultural nonpoint source pollution of surface and ground water resources.</b>	by improving or maintaining riparian and watershed function	Moderate support, research needed on more soils and sites.
	by minimizing deposition or flow of animal wastes into water bodies	Strong support, but would benefit from models.
	by minimizing animal effects on stream bank stability	Strong support.
	by providing adequate litter, ground cover and plant density to maintain or improve infiltration capacity of the vegetation	Strong support in concept, but responses need to be quantified for a range of soils and sites.
	by providing ground cover and plant density to maintain or improve filtering capacity of the vegetation	Strong support, but responses need to be quantified for a range of species and mixtures.
	by minimizing concentrated livestock areas, trailing, and trampling to reduce soil compaction, excess runoff, and erosion	Strong support and a range of practices to minimize soil damage, but few to restore soil condition.
<b>Protect air quality by reducing nitrogen emissions (ammonia and NO<sub>x</sub> compounds) and formation of atmospheric particulates.</b>	by reducing accelerated soil erosion	Strong support, would benefit from use of models.
	by minimizing concentrated livestock areas to enhance nutrient distribution and improve ground cover	Strong support, but needs to be integrated with plants and their growth habits.
	by improving carbon sequestration in biomass and soils	Strong support, would benefit from use of models to quantify relationships.
	by application of soil nutrients according to soil test to improve or maintain plant vigor	Strong support for most monocultures, need more research on mixtures.
<b>Maintain or improve physical, chemical, and biological condition of the soil.</b>	by applying and managing nutrients in a manner that maintains or improves the physical, chemical, and biological condition of the soil	Strong support intuitively based on annual crops, but needs verification using long-term perennials.
	by minimizing the use of nutrient sources with high salt content unless provisions are made to leach salts below the crop root zone	Strong support, but it does not appear to be a problem unless excess rates applied.
	by not applying nutrients when the potential for soil compaction and rutting is high	No support, research needed because perennials can become compacted, but are not tilled.



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Many studies were conducted for only 2 or 3 yr, which is insufficient for ecological adjustment to achieve a near steady state”

## SYNOPSIS AND PERSPECTIVES CHAPTER 6

Following the focused assessment on the conservation standards, a general cross-cutting overview was developed that also included a futuristic perspective.

### General Findings

- Nearly all studies were conducted on pastures or field plots on good soils with little consideration of topographic features or potential to transfer the response and environmental data to the landscape or watershed level.
- Many studies were conducted for only 2 or 3 yr, which is insufficient for ecological adjustment to achieve a near steady state for conditions being evaluated.
- Specific growth characteristics of most pasture and hayland species are known, but field responses were not always consistent with expectations, whether plant types were harvested mechanically or by grazing.
- Cost effectiveness of implementing a conservation standard was rarely considered in terms of returns to the land owner or values of ecosystem benefits for the landowner and public.
- No research was found that evaluated the production and ecosystem costs that would accrue if the practice was not implemented.
- In many cases the literature showed that a certain management scheme would improve economic productivity, yet the practice may not deliver desired ecosystem services.

- Very rarely was management designed to provide cost of environmental or ecosystem services relative to income from production of forage or animal product.
- When research is minimal or not available, implementation of a practice depends largely on experience and knowledge of local conditions from agency personnel.
- Little research assesses practices that reduce risk of failure; such research is needed to calculate costs during practice implementation.
- Authors sought research on emerging and future ecosystem interests; usually new methods were suggested to get more or better information to quantify the responses.
- The standards are updated about every 5 yr, but new technologies, especially analytical methods, and increased public interest in ecosystem outputs change more rapidly.
- Future research should be longer term and more comprehensive; however, this will exacerbate the time lag from perceived need to having the correct data to address the need.
- Ecosystem services need to be explicit in future standards to provide more focus.
- Most practices are considered long term and would benefit from monitoring the success on a periodic basis and providing assistance on using adaptive management to correct shortcomings.
- The agency will benefit from public education and widespread success stories.



Models will help in planning conservation practices and determining variables to monitor while the practice is operational.”

**Implications:** Evaluation teams assessed a single practice standard in a professional manner. There was good science support for most purposes and criteria, especially on factors affecting production. Unfortunately, because of a lack of credible methodologies and priority for determining value of services, the research over the past few decades used to develop production practices was rarely coupled with quantifiable measures or comparisons with economic or social values of the conservation practices or ecosystem services. The teams also could not evaluate expected or desired durations of effective functioning after the practice was implemented. Some newer publications addressed the more comprehensive issues.

Future criteria for practice standards for multiple purposes should explain expected outcomes more quantitatively, as well as provide estimates of the lifetime of the practice assuming adaptive management. Monitoring of practices to ensure they are working, and then using adaptive management to assist the landowner correct and extend the life of the practice will help maintain credibility and increase cost effectiveness to demonstrate fiscal responsibility. Is it more cost and outcome effective to have one practice that lasts 20 yr or to have two sites of the same practice that each last 10 yr? Models will help in planning conservation practices and determining variables to monitor while the practice is operational. The model could also guide adaptive management toward the most cost-effective way to restore or maintain the practice.

There are many facets involved in the analyses of a practice and the outcomes are not always consistent through the life of a practice. For example, ecosystem risks during establishment may be very high for a species that has relatively low risk when established. Therefore, using forage plantings for a longer time in a rotation or managing to extend the life of a quality pasture reduces the amount of reseeding occurring each year to establish new stands. And one management approach for riparian areas may favor water quality over certain wildlife species, whereas another approach may favor wildlife over water quality. Keeping a pasture shorter may favor some ground-nesting species, but have increased runoff and effects on water quality and fish in a nearby stream. Models may help in understanding the interactions and give guidance to trade-offs and optimizing the solution.

Overall, it is imperative to understand expanding public goals and expectations from agriculture, beyond food, to management of natural resources in a sustainable way. As personal incomes increase, public expectations will continue to expand



from having sufficient food to having it produced in a way that first preserves the environment and then provides other ecosystem services, especially for social issues and wildlife. Each step usually leads to higher food costs that are recognized and accepted. Already there are major issues emerging as agricultural and public priorities including pending climate change, water quantity and quality issues, biofuel issues, energy needs for food supplies, and values of environmental and ecosystem services. It is not known how much the public will pay for these.

With modern access to electronic information sources, improved media coverage of issues, and social media, both the public and agricultural community will usually be aware of emerging issues and likely will develop strong opinions before sufficient research has been conducted. The U.S. citizenry is already moving rapidly along this continuum; the challenge will be to stay ahead of the movement, because it will take even more years to develop the research base and recommendations. Intermediate-term solutions will depend on educated and talented agency personnel who can provide credible science-based recommendations until more specific data are assembled and evaluated. Success stories abound and should be used in public educational programs as USDA-NRCS adopts and implements the new foundations for conservation standards.





## CHAPTER

# 1

# Pastureland and Hayland in the USA: Land Resources, Conservation Practices, and Ecosystem Services

Matt A. Sanderson,<sup>1</sup> Leonard W. Jolley,<sup>2</sup> and James P. Dobrowolski<sup>3</sup>

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Government agencies increasingly are tasked to account for money invested in conservation...”

# Pastureland and Hayland in the USA: Land Resources, Conservation Practices, and Ecosystem Services

# 1

Matt A. Sanderson, Leonard Jolley, and James P. Dobrowolski

Forage, grasslands, and grazing lands constitute more than two-thirds of all agricultural land in the USA. Indeed, some view these lands as “the cornerstone of all agriculture” (Wedin and Fales, 2009). Pasture and hayland account for 73 million ha in the USA (Figs. 1.1 and 1.2) and provide several ecosystem goods and services. Increasing and sustaining these ecosystem goods and services (e.g., conserving and protecting soil, water, and air resources) usually requires the investment of public resources. Government agencies increasingly are tasked to account for money invested in conservation policies, programs, and practices in quantitative terms of environmental outcomes (e.g., how much has water quality or soil quality been improved?) rather than simple numeric metrics (e.g., kilometers of fence installed, hectares of land treated). Although not perfected, there are methods being developed and evaluated to quantify the outcome in monetary values (Brookshire et al., 2010).

The Conservation Effects Assessment Project (CEAP) is a multiagency effort to quantify scientifically the environmental outcomes of conservation practices used by private landowners that are supported by U.S. Department of Agriculture (USDA) and other conservation programs (Duriancik et al., 2008). The purpose of CEAP is to “help policy makers and program managers implement existing and design new conservation programs to more effectively and efficiently meet the goals of U.S. Congress and the Administration” (James and Cox, 2008). Outcomes from CEAP will also inform scientists and practitioners of policy needs and expectations of policy makers to account for the ecosystem services and environmental outcomes intended by specific conservation practices. In addition, CEAP will shed light on gaps in scientific knowledge needed to support conservation outcomes and provide insight as to how to attack researchable problems regarding these practices.

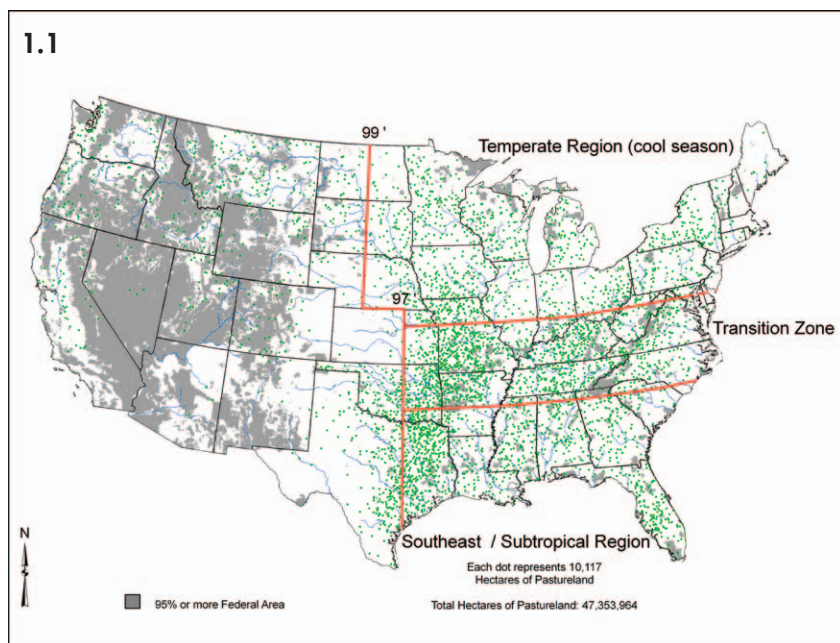
Principal components of CEAP include 1) a national assessment of conservation practices, 2) studies of conservation practices up to the watershed level, and 3) detailed bibliographies and syntheses of scientific literature regarding environmental outcomes of specific conservation practices. Assessments were conducted within three main agroecological resource areas: croplands, wetlands, and grazing lands, including effects on wildlife in each. These assessments contribute to determining the effectiveness of current programs and the process of building the science base for conservation, which includes research, monitoring and data collection, and modeling (Duriancik et al., 2008).

Earlier CEAP literature syntheses focused on cropland and wildlife. The cropland synthesis documented the environmental outcomes of soil, water, nutrient, and pest management conservation practices applied to rain-fed and irrigated cropland (Schnepf and Cox, 2006). A follow-up literature synthesis focused on multidisciplinary analyses of achieving realistic cropland conservation goals at watershed and landscape scales (Schnepf and Cox, 2007). The wildlife synthesis focused on the Conservation Reserve Program (CRP) and its resultant effects on fish and wildlife (Haufler, 2005, 2007).

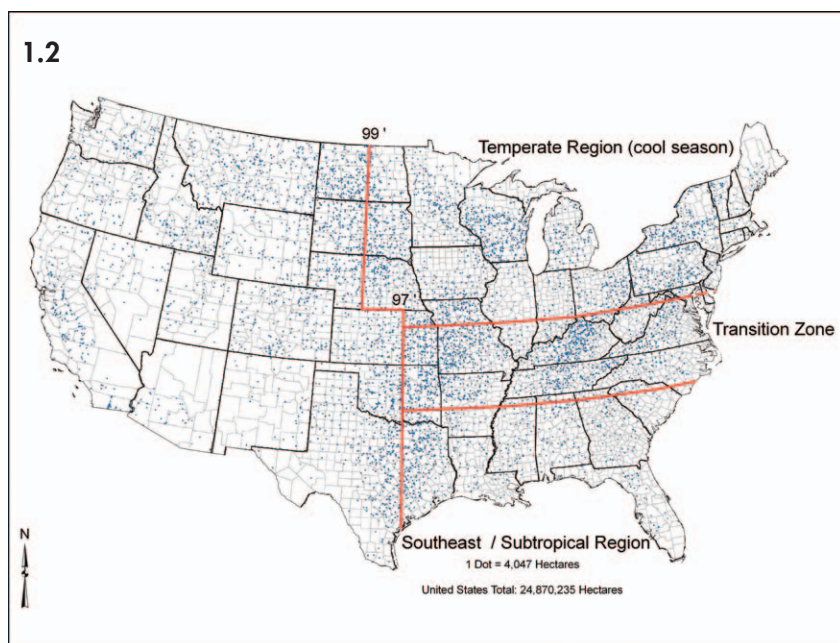
Because most CRP land is grassland, the conclusions and recommendations from the wildlife syntheses are particularly relevant to managed forage and grasslands. For example, grassland managed for the CRP has benefited grassland birds, especially in the Great Plains (Johnson, 2005). Grassland in CRP, however, often is cut one or two times for weed control, but not harvested (except for hay during drought emergencies), which differs in timing of cutting and residue management from normal pasture and hayland practices. This difference restricts direct transfer of management



The total economic value of forage and grasslands that support ruminant animal production is estimated at about \$45 billion annually. Photo: USDA.



**FIGURE 1.1.** Area of pastureland in different regions of the USA. See Table 1 for states grouped into the temperate (cool season) region, transition zone, and the southeast and subtropical regions. Source: USDA-NRCS (2003).



**FIGURE 1.2.** Area of forage/hayland in different regions of the USA. Source: USDA-NASS (2009).

effects on ecosystem services from CRP land to hay and pasture areas.

In this literature synthesis, individual chapters address four USDA–National Resources Conservation Service conservation practices: forage and biomass planting (practice standard

512; formerly pasture and hayland planting), prescribed grazing (practice standard 528), forage harvest management (practice standard 511), and nutrient management (practice standard 590). As a prelude to the chapters on individual conservation practices, in this chapter we describe pasture and hayland resources in the USA, including national trends; touch on the history of conservation practices on pasture and hayland; and introduce key conservation challenges on pasture and hayland.

## PASTURE AND HAYLAND: EXTENT AND VALUE

Pastureland is “land devoted to the production of indigenous or introduced forage for harvest by grazing, cutting, or both” (Allen et al., 2011). There are 48.5 million ha of pastureland in the USA (Fig. 1.1) and 25.1 million ha of land used for production of hay and other conserved forage (except row crops for silage) (Fig. 1.2; USDA–National Agricultural Statistics Service [NASS], 2009). Pastureland is concentrated in the humid eastern half of the USA (east of 99° longitude; Vough, 1990; Barnes and Nelson, 2003), whereas land for production of hay and other conserved forage is distributed more broadly across the USA (Figs. 1.1 and 1.2). In addition, there are about 1 million ha of irrigated pastureland in the western USA. Alaska has 4000 ha of pastureland and 8100 ha of hayland. Hawaii has 15,000 ha of pastureland, and Puerto Rico has 70,000 ha.

Cool-season temperate forage and grasslands occupy much of the northeastern USA, the lake states, midwest, and parts of the northern Great Plains. This includes the traditional dairy regions of the upper midwest and the northeast, along with significant production of beef cattle with lesser production of small ruminants (sheep and goats) and horses. Cool-season perennial forages such as orchardgrass (scientific names of all plant species used in this chapter are given in Appendix III), alfalfa, smooth brome grass, and white clover predominate in this region. Moving southward, the vegetation changes to include more warm-season species in an area often referred to as the transition zone between the cool-temperate and subtropical grassland regions. This zone includes the tall fescue belt, with about 10 million ha of tall fescue that is often overseeded with red clover and managed

**TABLE 1.1.** Number of grazing livestock in states within climatic regions of the eastern USA. (USDA-NASS, 2009).

State	Cattle and calves	Horses and ponies	Sheep and lambs	Goats
<b>Temperate (cool-season) region</b>				
Connecticut	50,200	11,500	5800	4600
Illinois	1,231,000	79,500	52,400	33,700
Indiana	875,400	81,200	49,000	47,100
Iowa	3,982,000	71,200	209,300	56,000
Maine	88,200	12,200	10,900	5900
Massachusetts	46,800	20,600	11,800	8200
Michigan	1,048,200	101,100	81,700	27,800
Minnesota	2,395,200	90,100	144,600	36,800
Nebraska <sup>1</sup>	3,342,000	33,500	52,700	15,000
New Hampshire	36,900	9900	7700	3900
New Jersey	38,200	30,100	14,800	10,600
New York	1,443,300	85,000	63,200	39,900
North Dakota <sup>1</sup>	674,000	16,800	39,000	1500
Ohio	1,272,400	119,200	123,200	69,500
Pennsylvania	1,609,100	116,300	96,900	59,200
Rhode Island	5100	3500	1500	700
South Dakota <sup>1</sup>	2,570,000	35,600	200,400	4500
Vermont	264,800	13,300	13,900	6600
Wisconsin	3,373,900	120,000	89,600	55,900
Region total	24,346,700	1,050,600	1,268,400	487,400
<b>Transition zone</b>				
Arkansas	1,802,600	79,000	15,300	50,600
Delaware	21,000	4000	900	3500
Kansas <sup>2</sup>	3,335,000	71,300	60,700	27,400
Kentucky	2,395,400	175,500	37,000	98,200
Maryland	190,500	30,700	22,100	16,900
Missouri	4,292,700	149,200	77,000	96,400
North Carolina	820,200	78,400	27,700	98,400
Oklahoma <sup>2</sup>	1,680,000	127,600	51,500	61,500
Tennessee	2,122,000	142,000	29,800	131,000
Virginia	1,566,200	90,400	77,600	63,100
West Virginia	411,000	37,700	38,300	27,900
Region total	18,636,600	985,800	437,900	543,900
<b>Southeast/subtropical region</b>				
Alabama	1,187,200	87,100	16,900	80,400
Georgia	1,117,100	76,700	11,300	84,000
Louisiana	878,700	60,500	8700	21,600
Mississippi	987,300	65,300	8400	30,600
Florida	1,711,000	120,600	13,000	57,700
South Carolina	401,000	43,300	7900	43,900
Texas <sup>2</sup>	5,110,000	231,000	60,700	365,000
Region total	11,392,300	684,500	126,900	683,200
Eastern U.S. total	54,375,600	2,720,900	1,833,200	1,714,500
Contiguous U.S. total	96,347,900	4,028,800	5,812,200	3,140,500

<sup>1</sup>Data from counties east of the 99th meridian. <sup>2</sup>Data from counties east of the 97th meridian.

CEAP will shed  
light on gaps  
in scientific  
knowledge”



In contrast with rangeland, pastureland management is relatively intensive and technology based”

mainly for beef cattle production. The south-eastern region (along with Hawaii and Puerto Rico) relies heavily on warm-season grasses such as bermudagrass and bahiagrass, along with cool-season annual legumes and grasses (e.g., arrowleaf clover and annual ryegrass) to fill forage gaps in autumn and winter.

Of the 109 million head of livestock that utilize forage and grazing land in the USA, about 61 million head are in the eastern half (Table 1.1). Approximately 45% of these eastern livestock are in the cool-temperate region, 34% in the transition zone, and 21% in the southeast and subtropical region. Alaska, Hawaii, and Puerto Rico account for about 400,000 head of grazing livestock.

In contrast with rangeland, pastureland management is relatively intensive and technology based, commonly with inputs of seeds, fertilizers, and pesticides. Most plant species present are not native, and pastureland may be periodically renovated or replanted by a variety of techniques. Stocking densities on pastureland vary from 0.7 to 2 ha per grazing animal (Burns and Bagley, 1996). By contrast, rangelands predominate in the drier western half of the USA, with a few exceptions such as the flatwoods rangeland of Florida, longleaf pine grassland in Alabama and Louisiana, and scattered areas of fragmented native grasslands.

The traditional goods from forage and grazing lands include food, feed, fiber, forest products, milk, and meat. The total economic value of forage and grasslands used in ruminant animal production is estimated at about \$44 billion (Table 1.2). Hay and other conserved forage production account for \$18 billion of farm income (USDA-

NASS, 2009). In addition, there are numerous ecosystem services provided by forage and grazing lands, including reduced soil erosion and improvements in water quality, wildlife habitat, and air quality. There often is little or no direct economic return to the land manager, yet society is rapidly recognizing that the intrinsic values of these ecosystem services are important for the public good and that there is a need for them to be provided.

### NATIONAL TRENDS IN FORAGE AND GRAZING LANDS

The estimated 238 million ha of permanent grassland pasture and rangeland account for 26% of all U.S. land and half of the agricultural land (Lubowski et al., 2006). Adding cropland used as pasture (25 million ha), woodland grazing land (54 million ha), and that harvested for conserved forage (25 million ha) to the permanent grassland area indicates total forage and grazing land equals about 342 million ha, or 38% of the total U.S. land area and more than two-thirds of all agricultural land (Lubowski et al., 2006). This total does not include land grazed before or after crops were harvested.

About 7% of the total permanent grassland pasture and rangeland is in the eastern half of the USA (Fig. 1.3). In the humid south, cropland pasture and forested grazing predominate. Nationwide, grazed woodland includes open-canopy forest, land reverting to forest, and other woodlands that contain grazable grass or other forage. Grazable woodlands dominate parts of the humid south as a function of productivity potential, demand for grazing land, understory species composition during expansive growth

TABLE 1.2. Forage value in livestock diets in the USA. Adapted to 2008 cash receipts from Barnes and Nelson (2003).

Animal type	Feed costs as a proportion of receipts	Proportion of feed units fed as forage	Forage value as proportion of feed costs <sup>1</sup>	2008 cash receipts <sup>2</sup>	Forage value <sup>3</sup>
				Billions of dollars	
Beef cattle	0.70	0.83	0.581	48.2	28.0
Sheep+wool	0.70	0.91	0.637	0.45	0.29
Dairy cattle (milk)	0.50	0.61	0.305	34.8	10.6
Horses <sup>4</sup>	0.7	0.6	0.42	11.8	5.0
Goats	0.7	0.9	0.63	0.25	0.16
Total forage value					44.0

<sup>1</sup>Calculated as column 2 multiplied by column 3. <sup>2</sup>USDA-NASS (2009). <sup>3</sup>Calculated as 2008 cash receipts (column 5) multiplied by value in column 4. <sup>4</sup>American Horse Council (available at <http://www.horsecouncil.org/nationaleconomics.php> [verified 24 Jan. 2011]).

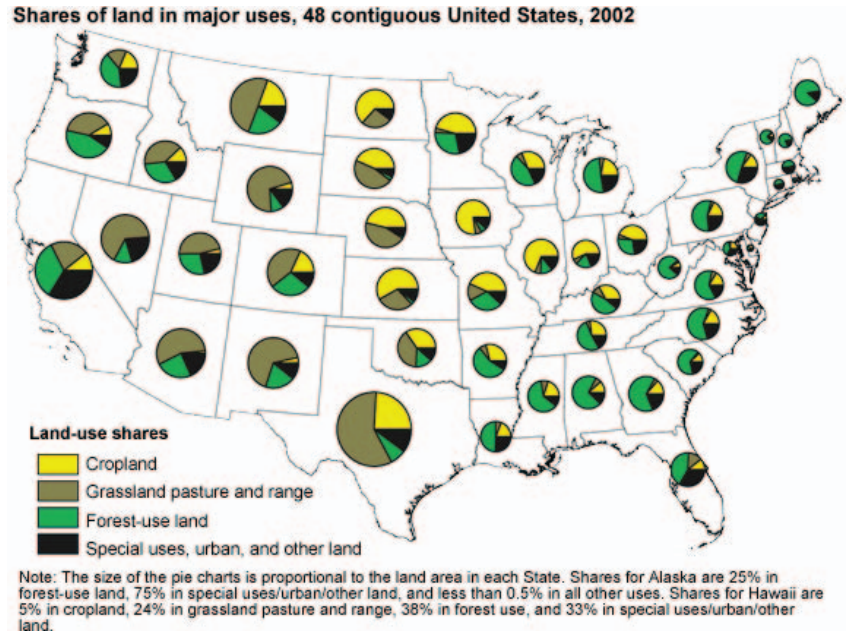
of the trees, and density of overstory. On the southern and southeastern coastal plains woodland values are enhanced by grazing open stands of pine almost year-round in many climatic regimes. Upland hardwoods with dense canopies, typically covering the northeast region of the USA, produce less forage; however, these landscapes at times may be grazed.

During 1997–2002, cropland pasture decreased 1%, reducing total grazed area by 2.4 million ha, about a third of this via conversion to CRP land. Approximately 1.6 million ha changed from pasture to forest. Cropland pasture, permanent pasture, and rangeland decreased by 5.3 million ha, which was about 55% of the total loss of 9.7 million ha of agricultural land identified in the National Resources Inventory (USDA-NRCS, 2003). Cropland used for pasture is typically part of a rotation between crop and pasture use, with variable rotation periods. Two-thirds of the 25 million ha of cropland pasture were located in the southern plains, corn belt, northern plains, and Appalachian regions. Much of the cropland pasture in the south and plains states occurs on more marginal lands.

Trends in pasture, rangeland, cropland, and woodland used for grazing indicate that total grazing land decreased by about 108.5 million ha (about 25%) from 1945 to 2002 (Lubowski et al., 2006). This land-use change may reflect a transition to urban, recreational, wildlife, and environmental land uses. One exception to the long-term trend is that permanent pastureland increased by 0.8 million ha in the southeastern USA, mostly from land classified previously as grazable woodland. In other parts of the USA, grazable woodlands decreased by nearly 58%. This long decline in grazable woodland might be explained by fewer and larger farms, greater woodland canopy density, and greater efficiencies in both livestock and woodland management. All of these factors have been especially important in the southeastern USA, where high proportions of woodland are grazed (Lubowski et al., 2006).

### HISTORY OF CONSERVATION PRACTICES ON PASTURE AND HAYLAND

Water runoff and some associated soil loss from agricultural land have been observed for centuries, but the soil loss was not quantified. But



**FIGURE 1.3.** Proportions of cropland, grassland pasture, and range, forest-use land, and other land in the 48 contiguous states (Lubowski et al., 2006). Used with permission.

when measured, it was learned that pasture and hayland were much more effective in reducing runoff and associated soil loss than were row crops. Federal conservation practices developed and applied to cropland and to pasture and hayland date back to the 1930s, which paralleled the beginning of government agencies such as the USDA-NRCS (Bennett, 1939; Helms, 1990). Early prescribed practices focused on reducing overgrazing on pasture and rangeland. The theme of grassland agriculture using permanent vegetation as a conservation practice, using hayland in crop rotations, and applying conservation practices to pastures and hayland emerged in the 1930s and runs through several influential college textbooks on pasture and forage management (e.g., Wheeler, 1950; Hughes et al., 1951; Miller, 1984; Barnes et al., 2003, 2007).

Research on conservation practices also dates back to the 1930s with the establishment of soil conservation experiment stations and collaboration between the Soil Conservation Service (progenitor of the USDA-NRCS) and the Bureau of Agricultural Economics (progenitor of the USDA Economic Research Service [ERS]) to assess benefits of conservation practices. Some of this research was documented in early USDA bulletins (e.g., Hoover, 1939; Bennett, 1951; Dale

and Brown, 1955). During the 1970s, the Clean Water Act stimulated research on conservation practices to protect water quality.

Despite several decades of improving management on pasture and haylands through use of conservation practices, significant conservation issues remain and new ones have emerged. There are an estimated 30 million ha of pasture and hayland in the USA that would provide greater environmental benefits from some form of conservation treatment, such as prescribed grazing, pasture/hayland planting, and nutrient management (USDA-NRCS, 2004). Conservation practices to protect soil and water resources are a critical part of pasture and hayland management because much of this land is sloping, is classified as marginal for cropland, and has a small margin for error in management (Helms, 1997).

### RESOURCE CONCERNS ON PASTURE AND HAYLAND

The principal resource concerns addressed in conservation programs include soil, water, air, plants, animals, and human resources (USDA-NRCS, 2010a). In addition, efficiency of energy use recently has been added to this list of resource concerns because of the costs of energy

and the new role of agriculture in producing renewable energy.

Mismanagement of pasture and hayland can reduce production and profit and harm the environment. For example, poor nutrient management on pastureland is estimated to contribute 37% of the phosphorus load from the Mississippi river basin into the Gulf of Mexico (Alexander et al., 2008). Grazing management that exceeds sustainable carrying capacity can degrade vegetation, enhance runoff, and impair water quality (Agouridis et al., 2005).

The 2008 Farm Bill outlines several voluntary programs that target resource concerns and conservation on forage and grazing lands, including:

**Conservation of Private Grazing Lands (CPGL).** Provides technical assistance to owners and managers of private grazing lands to implement grazing land management technologies, protect water quality, and enhance wildlife habitat, among other goals.

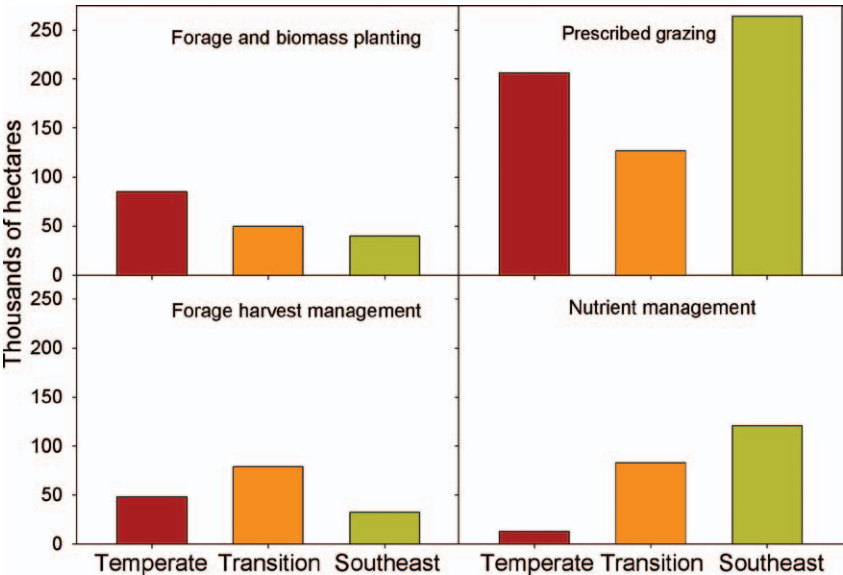
**Conservation Stewardship Program (CSP).** Compensates farmers for undertaking additional conservation activities and improving, maintaining, and managing existing conservation activities.

**Farm and Ranch Lands Protection Program (FRPP).** Aids local governments and nongovernmental organizations with purchasing conservation easements to protect agricultural use and related conservation values of land.

**Grassland Reserve Program (GRP).** Protects and restores grassland.

**Environmental Quality Incentives Program (EQIP).** Provides financial incentives to farmers to promote agricultural production and environmental quality as compatible goals. The program has placed added emphasis on organic production, including assistance for grazing systems.

These programs pay (or provide cost share) farmers to implement various conservation practices to address specific resource concerns. Of the four USDA-NRCS conservation practices addressed in this publication, prescribed grazing was the most widely applied practice during 2010 (Fig. 1.4). Prescribed grazing was applied

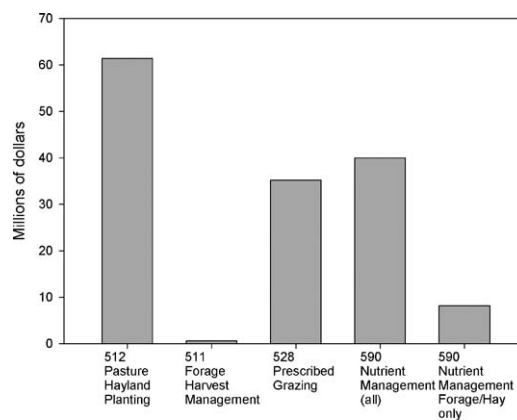


**FIGURE 1.4.** Pasture and hayland area in three principal regions of the USA to which selected USDA-NRCS conservation practices were applied in 2010. Data for prescribed grazing and nutrient management practices are for pastureland only. Regions are defined in Table 1.1. Data are from the USDA-NRCS performance reporting system.



to a total of 640,491 ha of pastureland with 41% of that area in the southeast, 32% in the temperate region, 20% in the transition region, and 7% in the western states. The greater application of prescribed grazing in the southeast may indicate that pastures (soils, stands of desired species) are more degraded, the growing season is longer and often year-round, and forage species are better adapted to rotational stocking than in other regions. There may also be more cost-share funding available for a high number of small farms in this region. The forage and biomass planting practice was applied predominantly in the temperate region where legumes are in short rotations and they suffer from winter injury. Forage harvest management was applied mostly in the transition region. The nutrient management practice was applied nearly entirely in the southeast and transition regions, perhaps because of the frequent use of poultry litter and other animal manures on pastures in these regions see (Wood et al., Chapter 5, this volume).

Comparable recent data were not available on the amount of government support for each of



Early conservation efforts on grazing lands started during the dust bowl days of the 1930s. Photo: USDA.

**FIGURE 1.5.** Government payments made for selected conservation practices implemented in the states east of the Missouri River as part of the Environmental Quality Incentives Program (EQIP). The EQIP program accounts for most of the NRCS conservation practice payments in the eastern USA. Data are totals for the years 2004–2008. Data for 590 nutrient management (all) apply to all classes of livestock and land uses. The data for 590 nutrient management (forage/hay land) apply only to forage and hayland use. Information provided by the Agriculture and Environment Program of Tufts University, Boston, MA.



Hay and other conserved forage production in the USA accounts annually for \$18 billion of agricultural receipts. Photo: USDA.

the four practices by region across all NRCS programs. Available information on funding for the Environmental Quality Incentives (EQIP) program during 2004–2008 in the eastern USA, however, shows that most of the funding supported forage and biomass planting (standard 512; formerly pasture and hayland planting; Barker et al., Chapter 2, this volume) and prescribed grazing (Fig. 1.5). Although about \$40 million went to nutrient management for all

classes of livestock and land uses in the eastern USA, only \$8.2 million of that amount could be attributed specifically to forage and hayland use. Only about \$500,000 went to forage harvest management.

## PRODUCTION CONCERNS ON PASTURE AND HAYLAND

Agriculture in the USA has changed dramatically since the early 20th century, with fewer but larger farms, higher capital costs, and a greater reliance on technology (Sheaffer et al., 2009). Forage and grasslands also are viewed as important sources of biomass feedstock for use in producing renewable energy (Sanderson et al., 2009). Despite these changes, the production concerns of primary interest for pasture and hayland are little changed and include generating adequate amounts of forage of an acceptable nutritive value to sustain various classes of livestock and generate a profit for the farmer. The latter concern is uppermost in the farmer's mind, especially when prices of agricultural outputs are low and volatile.

Adopting and improving grassland management practices can lower production costs and improve the farmer's net income (Sheaffer et al., 2009). Forage yields have increased minimally over the past 50 yr, but there have been small increases in forage quality and improvements in grazing management (Nelson and Burns, 2006). There have also been advancements in reducing stored forage needs for beef cows by extending the grazing season by using deferred grazing, improved nutrient management, and overseeding cool-season species into warm-season pastures in the south.

To achieve production goals, the farmer may replant forage stands with better adapted, more productive, or higher-quality species and varieties; enhance soil fertility through applications of commercial fertilizer or livestock manure; modify the harvest or grazing management to optimize utilization; or control invasive and destructive weeds and pests. Each of these management interventions has implications regarding the soil, water, air, plant, animal, human, and energy resources in the system. For example, renovating pastures or hay fields via tillage may pose soil-erosion risks; poor timing and placement of nutrients from fertilizer or manure may increase

runoff or leaching from fields; and intensifying grazing or harvest management may reduce vegetation cover or change the plant community composition. Thus, it is critical that land managers consider how to make conservation practices an integral part of their pastureland and hayland management plan to achieve production and conservation goals simultaneously.

### Emerging Emphasis on Ecosystem Services of Pasture and Hayland

Forage and grasslands have long been recognized for multiple services such as soil conservation, water-quality protection, and pleasing aesthetics, among many others (e.g., see USDA, 1948). These multiple services are now recognized in the concepts of *ecosystem functions* and *ecosystem services*, which have received much attention (Daily et al., 1997; Lemaire et al., 2005; Millennium Ecosystem Assessment, 2005). Ecosystem functions are the “habitat, biological, or system properties or processes of ecosystems,” whereas ecosystem goods and services include the “benefits human populations derive, directly or indirectly, from ecosystem functions” (Costanza et al., 1997). Ecosystem goods and services have been classified into four main categories: 1) provisioning services, which include products from ecosystems such as food, fiber, and fuel; 2) supporting services, such as primary production and nutrient cycling that enable all other ecosystem services; 3) regulating services such as climate and flood regulation; and 4) cultural services, which include nontangibles such as aesthetic, spiritual, educational, or recreational experiences (Fig. 1.6). These concepts are often discussed in the context of multifunctionality, which refers to the joint production of goods (e.g., agricultural commodities) and ecosystem services (Jordan et al., 2007).

Currently, the USDA-NRCS Conservation Stewardship Program rewards farmers for managing land for multiple ecosystem services, such as soil conservation, water-quality protection, and carbon (C) sequestration (USDA-NRCS, 2010b). The USDA National Organic Standards emphasize pasture utilization not only for feed production but also for animal well-being and product quality (USDA–Agricultural Marketing Service [AMS], 2010). And, the final rule for the Grassland Reserve Program explicitly defines ecosystem services from grasslands as “Functions and values of grasslands and shrublands means

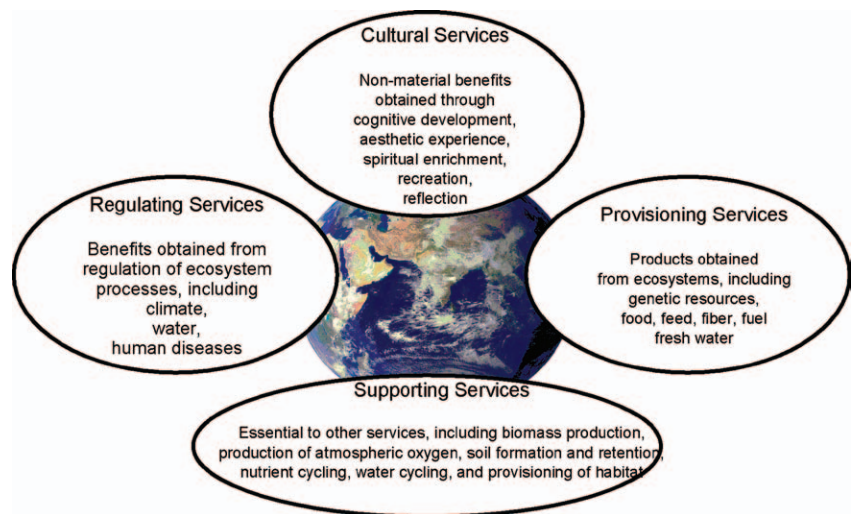
ecosystem services provided including: domestic animal productivity, biological productivity, plant and animal richness and diversity and abundance, fish and wildlife habitat (including habitat for pollinators and native insects), water quality and quantity benefits, aesthetics, open space, and recreation” (Federal Register, 2009).

It is clear that forage and grazing lands increasingly are expected to provide ecosystem services beyond the traditional provision of food, feed, and fiber (Sanderson et al., 2009). A partial list of potential ecosystem functions, goods, and services from pastureland is in Table 1.3. Forage and livestock production (provisioning services) provide obvious economic benefits from pasture and hayland (Tables 1.2 and 1.3), along with environmental and social dividends (support, regulatory, and cultural services), such as landscape diversity and open space. Fishing and hunting on these lands provide revenue through sales of licenses, sporting equipment, and access rights while contributing to healthy wildlife populations. In the future, pasture and hayland may supply biofuel feedstocks, leading to reduced greenhouse gas emissions and lesser dependence on fossil fuels. A key feature will be to develop and adopt management systems that optimize the multiple goals to meet priorities of the landowner and the public.

Forage and grazing lands rely on permanent vegetation cover to reduce soil erosion and protect



it is critical that land managers consider how to make conservation practices an integral part of their pastureland and hayland management plan”



**FIGURE 1.6.** Main categories of ecosystem goods and services. Graphic courtesy of Alan Franzluebbers, USDA-ARS, Watkinsville, GA. Earth image from NASA Goddard Space Flight Center (<http://visibleearth.nasa.gov/>).



Social pressures, environmental concerns, and regulations will continue to challenge farmers and ranchers”

**TABLE 1.3.** Ecosystem goods and services from pasture and hayland and their postulated economic, environmental, and social dividends (adapted from Table 1, pp. 11–13 of the Sustainable Rangelands Roundtable, 2008). The categories of “Economic,” “Environmental,” and “Social/cultural” are somewhat equivalent to the categories of “Provisioning,” “Supporting/Regulating,” and “Cultural” services, respectively, as defined by the Millenium Ecosystem Assessment (2005).

Ecosystem good or service	Dividends		
	Economic	Environmental	Social/cultural
Forage production for livestock	Sale of feed Hay, forage production	Landscapes for biodiversity Clean air and water Carbon sequestration Some plants (e.g., legumes) enrich soil	Open space Rural communities dependent on forage–livestock systems
Livestock production for humans	Sale of meat and fiber products Farming operations Economic base for rural communities	See forage production above Recycling of nutrients	Satisfaction derived from farming as a way of life Serenity of pastoral scenery Open space
Fishing and hunting Bird watching	Sales of licenses, gear, guide services Access rights on private or public lands	Promotion of healthy wildlife populations Maintenance of biodiversity Control of hunted populations	Pleasure involved in fishing and hunting Opportunity to observe wildlife
Clean water	Satisfaction of household, agricultural, and industrial needs Sale of bottled water Income from recreation	Quality of aquatic habitat Drinking water for wildlife Rejuvenation of riparian areas	Aesthetics of unpolluted water Pleasure derived from recreation
Biofuel feedstocks	Sale of the feedstock and resulting biofuel	Depending on feedstock: biodiversity maintenance, soil enrichment, carbon sequestration, greenhouse gas mitigation	Reduced dependence on fossil fuels

water quality, support symbioses (e.g., rhizobia and mycorrhizae) to supply some nutrients, and provide an aesthetically pleasing landscape. Grassland systems can also contribute to biodiversity, soil-C storage, and greenhouse-gas mitigation (Krueger et al., 2002). For example, maintaining biodiversity is a desired ecosystem service. Grasslands can be important reservoirs of plants, insects, and other organisms (Pimentel et al., 1992; Sanderson et al., 2004; Jog et al., 2006). Plant species diversity can be exploited to improve grassland production (Soder et al.,

2007) and resist weed invasion (Tracy et al., 2004; Sheley and Carpinelli, 2005).

Social pressures, environmental concerns, and regulations will continue to challenge farmers and ranchers to grapple with managing pastures and haylands to provide additional ecosystem services, including biodiversity conservation, C sequestration, mitigation of greenhouse-gas emissions, and bioenergy production (Jordan et al., 2007; Tubiello et al., 2007). These pressures, issues, and regulations have already led society demands for



The permanent vegetation cover on forage and grasslands intercepts rainfall to reduce impact and soil erosion, produces dense roots that hold soil and improve infiltration, filters water, and sequesters carbon in the soil organic matter. Photo: USDA.

a greater public role in agricultural practices for production and land management, and a greater degree of government accountability for resources invested in conservation programs.

The importance of forage and grazing lands in environmental stewardship was emphasized in a national report by the American Forage and Grassland Council (AFGC) that



The science behind the conservation practices...needs to be assessed. ”

identified several priority needs related to environmental protection and resource conservation (AFGC, 2001). Among the priorities were innovative grazing systems, flexible and dynamic nutrient management plans, management to increase carbon sequestration, and practices to conserve biodiversity. Thus, the science behind the conservation practices purported to provide these benefits and the magnitude of the ensuing benefits needs to be assessed. The next four chapters provide syntheses of the scientific literature related to forage and biomass planting (practice standard 512; formerly pasture and hayland planting), prescribed grazing (practice standard 528), forage and harvest management (practice standard 511), and nutrient management (practice standard 590).

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## CHAPTER

# 2

# Forage and Biomass Planting

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Even though good management might be used, the establishment period has a risk of failure.”

# Forage and Biomass Planting

David J. Barker, Jennifer W. MacAdam, Twain J. Butler, R. Mark Sulc

## INTRODUCTION

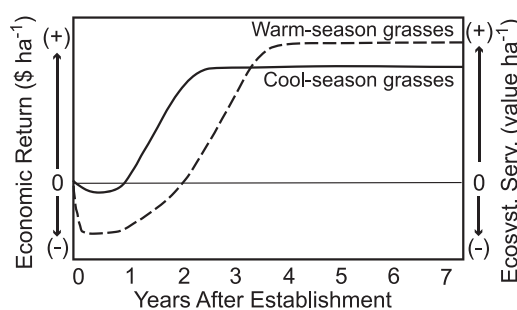
Forage and biomass species offer many benefits for conservation. More specifically, these species can be grown for grazing, hay, silage, biofuel, or industrial use and are among land-use options available to generate economic return and provide other agroecosystem services. Once established, these perennial species protect soil from erosion, improve water infiltration, reduce runoff, retain nutrients that might otherwise enter a waterway, provide shelter and sustenance for wildlife, build soil organic matter, increase soil nitrogen (N) through root and nodule turnover, support food and biofuel production, ensure food security, add to farm income, and contribute to the quality of rural life.

One dilemma of any planting is that even though good management might be used, the establishment period has a risk of failure because of factors such as wind and water erosion, disease and insects, hard seed, slow seedling growth, weed invasion, drought, or frost. Every establishment is likely to have a short period of production and financial loss, as well as negative environmental impact; however, it is the long-term positive benefits that make these short-term negative impacts tolerable (Fig. 2.1). These up-front costs of financial expenditure, lost production, and environmental disturbance occur irrespective of establishment success or failure, so additional input to reduce the risk of stand failure is warranted (Bartholomew, 2005). It is well known that managers should rely on local data, previous experience, careful timing, and good management to minimize risk and economic loss. The literature is deficient in descriptions of establishment failures that frequently occur, most likely because it can be difficult to publish negative data.

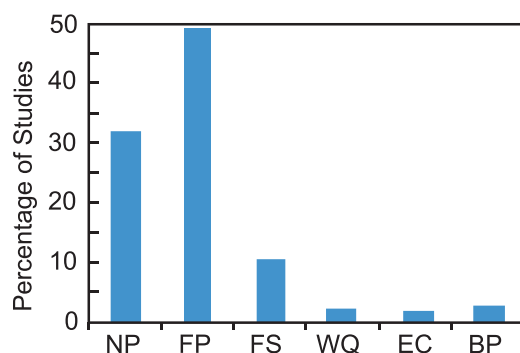
This chapter summarizes the research related to the Purposes and Criteria of the practices described in the Natural Resources Conservation Service (NRCS) Conservation Practice Standard, Forage and Biomass Planting, Code 512 (January 2010) (Appendix I); (Maderik et al., 2006). We address the establishment of grasslands intended for the purposes listed in Code 512 (Fig. 2.2) and focused the synthesis on plantings in the cool-season (temperate), transition, and subtropical zones of the eastern USA, and included intensively managed grasslands in the West (Figs. 1.1 and 2.3). This includes establishment of grazed forest and agroforestry mixes, grazed or harvested cover crops, perennial seedings for wildlife, and interseeding of annual species into perennial warm-season pastures. This excludes rangeland establishment, which was reviewed by Hardegee et al. (2011). Also excluded were seeding cover crops where the sole purpose was grain production; the seeding of grain



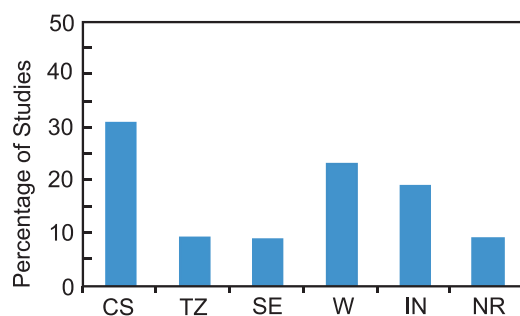
Birdsfoot trefoil 2 wk after spring planting in Utah (drill rows run left to right). Credit: Jennifer MacAdam, Utah State Univ.



**FIGURE 2.1.** Change in economic return from production following a new seeding for perennial plants as they achieve and maintain full production. Cool-season species often establish faster than warm-season grasses, and may differ in some ecosystem services. Associated contributions to ecosystem services (e.g., soil erosion, soil carbon, wildlife, and social values) are not well known or been assigned economic values. A short-term loss of production and/or services can be justified by the likelihood of benefits over the long term.



**FIGURE 2.2.** Percentage of 314 research publications on forage and grassland establishment based on the intended purpose. Purposes included no purpose stated (NP), improve forage production and animal nutrition (FP), balance forage supply (FS), improve water quality (WQ), enhance erosion control (EC), and biomass production (BP).



**FIGURE 2.3.** Percentage of 314 research publications on forage and grassland establishment based on the geographical region in which the research was conducted. Regions (see Fig. 1.1) included the cool season, mainly from northern and eastern states (CS), transition zone (TZ), southeast and subtropical (SE), west (W), international (IN), and no region stated (NR).

crops such as wheat (scientific names of all plant species used in this chapter are given in Appendix III) or corn where their secondary use might be for grazing; or Conservation Reserve Program (CRP) seedings, which were reviewed by Reeder and Westermann (2006).

In this chapter, establishment is defined as the period between seeding and utilization of the vegetation for its intended purpose, which is typically at the time full canopy cover is achieved. This period can be as short as 6 wk for rapidly establishing species in ideal conditions (e.g., annual ryegrass), or as long as 2–3 yr for slowly establishing species in a

harsh environment (e.g., big bluestem). In broader terms, establishment commences when the seed is placed into the soil and continues until development of a mature canopy. After establishment it may take as long as 7 yr for a mixed-species planting to achieve equilibrium and develop spatial patterns that are typical of a mature canopy. At the other extreme, some definitions of *establishment* consider only the time until seedlings have achieved enough leaf area for photosynthesis to be in a positive energy and nutrient balance, which might take as little as 21 d after emergence for rapidly establishing species (Ries and Svejcar, 1991).

This chapter comprises 11 sections derived from the Code 512 “Plans and Specifications,” and follows the sequence of decisions and operations necessary for a successful seeding. We begin with “Plans and Specifications,” followed by the preplant operations, “Selection of Species and Cultivars,” “Type of Legume Inoculant Used,” “Seed Source and Analysis,” “Fertilizer Application,” and “Seed Coatings and Pretreatments.” This is followed by the planting operations, “Site and Seedbed Preparation and Method of Seeding,” “Climatic Factors Affecting Time of Seeding,” “Rates of Seeding,” and “Seeding Depth.” We conclude with “Protection of Plantings,” divided into the subsections “Postseeding Management” and “Weed Control.”

## PLANS AND SPECIFICATIONS

Code 512 requires preparation of plans and specifications for planting of each site or management unit. In some cases, planning should start 12 mo prior to the actual seeding. Elements necessary to meet the intended purpose include selection of species, type of legume inoculant used, seed source and analysis, fertilizer application, site and seedbed preparation, method of seeding, time of seeding, rates of seeding, protection of the planting, and supplemental water for plant establishment.

Important components of the planning process that are omitted from Code 512 are

1. Financial analysis of the costs and benefits for the planting, including a cash-flow plan.

2. Environmental analysis of the disruption to agroecosystem services, and the long-term benefits that can be expected.
3. Consideration of other improvement options. In some cases, a new seeding may not be necessary if sufficient plants remain that can be stimulated. Other adaptive management options such as fertilization (Chapter 5), appropriate harvest schedules (Chapter 4), or appropriate grazing methods (Chapter 3) can achieve grassland improvement in some situations. In these cases, agroecosystem services might be maintained by avoiding disruption resulting from re-establishment.
4. Identification and correction of management or environmental factors (e.g., poor drainage, weediness, low fertility, under- or overgrazing, or poorly adapted species or cultivars) that might have contributed to failure of the prior stand. For example, alfalfa plants release autotoxins to the soil that reduce root growth of alfalfa. Thus, alfalfa should not be seeded immediately following a prior alfalfa stand (Jennings and Nelson, 2002a, 2002b). Failure to complete this step increases risk of an unsuccessful establishment that will require another new seeding (Hopkins et al., 2000).
5. Consideration of additional operational details, including options for the use of seed coatings and pretreatments, and determination of the correct seeding depth.
6. The consideration of livestock production was implied in Code 512, giving the implication there is less emphasis on environmental conservation and the emerging importance of food sources and habitat for wildlife.

## SELECTION OF SPECIES AND CULTIVARS

The most significant benefit of a new seeding is the introduction of preferred species or cultivars that were sparse or absent in the previous stand. One complexity in species selection is the number of options that exist. The 363 publications summarized in this chapter included 162 grassland species, comprised of 70 legume species, 79 grass species, and 13 forbs (Table 2.1; Fig. 2.4). Most species have many cultivars (e.g., as many as 1000 for alfalfa) that add to the complexity.

Agronomic performance varies among cultivars. For example, in South Dakota, slowly establishing ‘Vernal’ alfalfa was more dependent on use of an oat companion crop for weed control than the faster establishing ‘Saranac’ (Hansen and Krueger, 1973). This said, the unavailability of a given cultivar, species, or even inoculum may severely limit a producer’s options in a given year.

The selection of species for establishment is determined by the ultimate purpose of the land area. Formulating a seed mixture of desired species is based on variation in the establishment characteristics of the species used (Brar et al., 1991; Barker et al., 1993). Seeding rates used in mixed seedings integrate the relative establishment characteristics and the long-term botanical composition desired (Blaser et al., 1952). The literature has many examples of changes in botanical composition during establishment in response to the stand management (Skinner, 2005). Comparative analyses indicate species and cultivars can be ranked for rate of establishment and competitiveness during establishment (Blaser et al., 1952). However, the very large number of species and cultivars, the proportions in which they can be mixed, and their complexity of interactions within a variable environment have not been researched in detail, making selection of species mixtures as much art as science.

## Species and the Code 512 Purposes

### *Livestock and Wildlife Nutrition and Health.*

In most cases, there is a trade-off between forage production and nutritive value for the purpose of livestock and wildlife nutrition and health (Collins and Fritz, 2003; Chapter 3 of this volume). Sometimes the most productive species (e.g., tall fescue or switchgrass) is not the highest-quality option. Less-productive species, such as timothy, blue grama, or white clover, may be suitable components of a pasture mixture through their contribution to forage quality. Some of these desirable species can be difficult to establish and maintain in the mixture. Nutritional needs of livestock are complex (Dougherty and Collins, 2003), but in general, the highest-quality forages will contain high energy and protein. Thus, the major criteria for species selection are the desired use



One complexity in species selection is the number of options that exist.”

**TABLE 2.1.** Summary of the literature on responses of plant species to establishment practices. Most commonly researched species accounted for > 50% of the functional group.

Functional group	Most commonly researched species	Additional species	Total species	Total studies <sup>1</sup>	Percent of total
		Number			
Perennial legumes	Alfalfa, white clover, red clover	15	18	269	35%
Annual and biennial legumes	Subterranean clover, arrowleaf clover, winter pea, crimson clover, hairy vetch, sweet clover	46	52	93	12%
Cool-season perennial grasses	Orchardgrass, smooth bromegrass, perennial ryegrass, tall fescue, crested wheatgrass, timothy	28	34	169	22%
Cool-season annual grasses	Oat, wheat	7	9	62	8%
Warm-season perennial grasses	Switchgrass, big bluestem, indiangrass	30	33	143	19%
Warm-season annual grasses	Crabgrass, millet, sorghum sudangrass	5	8	13	2%
Forbs	Chicory, turnip, plantain	10	13	24	3%
Total			167	773	

<sup>1</sup>Includes 314 publications (47 reviews and 267 research papers), averaging 3.5 species per publication.

of the established stand and not their ease of establishment.

Current emphasis has expanded the list of desirable features of a forage mixture to include environmental and wildlife benefits, which involves more complex decision making. Even generalized species recommendations for wildlife are difficult because of the number of different species and the variability in their food and habitat requirements. There is increasing information on the dual-purpose supply of forage to domestic and wildlife species. Herbivorous wildlife (e.g., deer, elk, horses, etc.) have nutritional requirements similar to those of domestic livestock (Fennessey and Milligan, 1987), and well-managed grassland often has better forage quality than the vegetation they might usually encounter. An excellent review by Harper et al. (2007) lists 92 references describing the establishment and use of warm-season species for mixed wildlife and biomass production in the midsouth USA.

For some wildlife, habitat quality can be more important than nutritional value per se. In this respect, the dense stands of most well-managed forage grasses restrict nesting and feeding, with more open stands being preferred by ground-dwelling birds (Vickery et al., 2001). In contrast, many native prairie grass species grow as spaced bunchgrasses and offer excellent bird habitat. Grasslands used by wildlife must also support the insect and rodent populations used as food by certain bird groups. Similar to nesting issues, dense grassland stands may increase the cover for rodents and insects and reduce habitat quality for predatory and insectivorous birds such as owls, sparrow hawks, and meadowlarks (Vickery et al., 2001).

Studies also have shown that biodiverse vegetation with many flowering species usually supports more insects and consequently more bird species (Tscharntke and Hans-Joachim, 1995; Dupont and Overgaard Nielsen, 2006). In Minnesota, species-rich grasslands, especially those mixtures that included legumes and cool-season ( $C_3$ ) grasses,

supported greater insect diversity (Siemann et al., 1988). In addition to species selection, stand management (e.g., timing of mowing, grazing, or harvesting) can be important in allowing expression of flowering, as well as avoiding the disruption of nesting. Such management can be important to offset losses of species richness in the planting mixture (Siemann, 1998), yet management to allow flowering is usually in conflict with the goal of producing high-quality forage, because the highest nutritional value of most forage species occurs prior to flowers being formed.

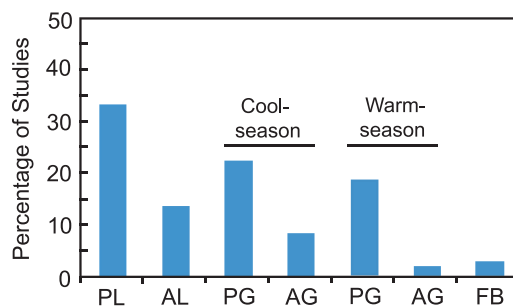
We found little research on establishment of multispecies mixtures, especially those developed with the multiple purposes of livestock production, environmental conservation, and wildlife benefits. As mentioned above, the first step should be to design the best mixture to achieve the multiple functions, and then use the management needed to maintain the proportions. The method for establishing that desired combination may include sequenced seeding, beginning with a rapidly establishing species to hold the soil followed by interseeding other species to develop the desired mixture gradually. These diverse goals and species also require technical information for adaptive management of the landowner to maintain the mixture as designed to achieve the desired purpose. Unfortunately, there were few establishment studies that focused on these longer-term concepts or goals.

**Forage Production and Seasonal Distribution.** Pasture species, and to a lesser extent, cultivars, differ in their growth patterns during the year. Species with contrasting growth patterns can be seeded together in the same pasture or separately in adjacent pastures within a grazing system (e.g., Moore et al., 2004) for the specific purpose of modifying the seasonal pattern of forage availability and quality. Early- and late-maturing cultivars of orchardgrass grown in separate fields on a single farm will spread the harvesting time for hay. There are several situations in which the diverse growth patterns of grassland species can be used to complement each other to ensure forage supply for a longer time period. Usually, the objective is to provide a year-round

supply of grazable forage to livestock; however, constraints from cold winters and dry summers reduce growth rates and prevent farms from achieving that goal. Thus, for most areas in the USA, farms are dependent on various systems to store forage (see Chapter 4). In such cases, species may be selected primarily for their ease of harvest and storage.

Optimal species for forage production differ among regions, districts, and even among fields within farms. Farmers should gain experience with new species and cultivars on small areas within their farms, because species and cultivar performance are sufficiently dependent on soil resources, slopes and aspects, livestock species, grazing management, and fertilization practices that their suitability can vary between adjacent farms. One strategy is for farmers to use mixtures of 3–10 species within a single sowing. Although this may increase the complexity of management to maintain each combination, the benefits of more species may include greater production and greater stability of livestock production (Blaser et al., 1952; Sanderson et al., 2004) or benefits to the environment and wildlife.

**Legumes vs. Cool-Season Grasses.** Most forage legumes have a higher temperature optimum for growth (25°C) than cool-season grasses (20°C; MacAdam and Nelson, 2003). Thus, in cooler conditions such as early spring or late autumn, cool-season grasses have a higher growth rate. In hotter conditions



**FIGURE 2.4.** Percentage of 314 research publications on forage and grassland establishment based on functional group of species evaluated. Groups included perennial legumes (PL), annual and biennial legumes (AL), cool-season perennial grasses (PG), cool-season annual grasses (AG), warm-season perennial grasses (PG), warm-season annual grasses (AG), and forbs (FB).



Dairy heifers grazing a perennial ryegrass pasture in Idaho. Credit: Jennifer MacAdam, Utah State University.

during summer (after cool-season grasses have flowered and are growing in a vegetative condition), legumes will generally have higher production. One of the benefits of grass-legume mixtures, in addition to N-fixation by legumes, is their complementary growth patterns. In most cases, adapted legumes and cool-season grasses are planted together and will co-exist in perennial stands with good management. In some cases where legumes are lost from a stand, legumes such as red clover or alfalfa can be no-till or frost-seeded (broadcast) into established vegetation (Taylor et al., 1969; Wolf et al., 1983; Schellenberg and Waddington, 1997).

**Cool- vs. Warm-Season Grasses.** Cool-season grasses are adapted to cool, moist conditions, such as early spring and late autumn, whereas warm-season grasses are better adapted to warmer, drier conditions that prevail in summer (MacAdam and Nelson, 2003). In mixture, the contrasting growth and agronomic requirements of these grasses can make it difficult to retain both functional groups in the desired proportions. More commonly, these species might be planted separately as special purpose areas within a farming system to provide feed during a period of deficit (Moore et al., 2004). In the midwest, the options for special-purpose warm-season pastures are 1) planting annual crops such as sorghum–sudangrass or tef or 2) planting perennial pastures with species such as switchgrass, big bluestem, or indiangrass.

**Autumn-Seeded Small Grains.** Annual small-grain species suitable for forage production include oat, barley, wheat, rye, and triticale. These species can be planted in autumn after early harvest of soybean for grain, corn for silage, or winter wheat, with the specific purpose of accumulating forage for later in winter when it might be grazed (Sulc and Tracy, 2007). Species vary in their tolerance to winter cold. Oat plants are not very frost tolerant and need to be harvested or grazed before or soon after temperatures fall below  $-5^{\circ}\text{C}$  to conserve yield and quality. At the other extreme, winter rye will survive most winters and have excellent early-spring growth.

#### **No-Till Seeding Into Perennial Pasture.**

One option for pasture renovation is to no-till cool-season species such as white or crimson clover into existing pastures of warm-season ( $C_4$ ) species such as bermudagrass. The primary benefits are to promote early- or late-season forage production and to improve forage quality. A common example in the USA is the establishment of annual or short-rotation (hybrid) ryegrass into bermudagrass (Swain et al., 1965). For the same purpose, ryegrass was no-till drilled into kikuyu pasture in northern New Zealand (Barker et al., 1990). Interseeding of cool-season grass or legume species into upright native warm-season grasses such as switchgrass or big bluestem has been less successful.

#### **Soil Erosion**

Grasslands have among the lowest rates of soil erosion compared to other land-use options (Owens et al., 1989). The mechanisms by which grasslands protect soil include, perennial vegetation that reduces rainfall impact on soil (Exner and Cruse, 1993), extensive root systems that die, leaving channels to enhance water infiltration, dense stands that slow surface water flow, dense and fine roots that hold soil particles, and greater earthworm numbers ensuring macropores for water infiltration (Owens et al., 1989). There is relatively little published information on differences in erosion among grassland species. One study found that adding smooth brome grass to an alfalfa stand had no effect on the erosion rates from the vegetation (Zemenchik et al., 1996). The dense vegetation of tall fescue provides better soil cover and has less runoff than do native warm-

season species (Self-Davis et al., 2003). In other studies, increased amounts of vegetative cover had the greatest effect on reducing erosion rates from pasture (see Chapter 4). If the vegetative cover is dense, relatively uniform, and has little or no bare ground present, the differences among species are negligible (Zemenchik et al., 1996).

### Improve Soil and Water Quality

The most important characteristics relevant to the quality of runoff water are the concentrations of suspended sediments and dissolved nutrients, and the presence of bacteria such as fecal coliforms. Nitrate and pesticides can also leach through the soil and into the ground water. The volume of water and the concentrations of the suspended or dissolved materials affect the total amount of these materials lost from an area. Since there is very little vegetation on tilled seedbeds during early stages of establishment, newly planted areas are more susceptible to runoff and leaching than established stands. However, no literature was found describing any effects of species on erosion or water quality during establishment. One article reported that contour planting (perpendicular to the slope) of forages reduced surface runoff compared to planting down the slope, but no data were presented (Decker et al., 1964).

Established grassland vegetation significantly improves water quantity and quality compared to forest or cropland (Dabney et al., 1994; Owens and Bonta, 2004; Vadas et al., 2008; Owens and Shipitalo, 2009). The effects of pasture species on water quality are negligible compared to the effects of pasture cover, and the management of that biomass via defoliation and timing of fertilizer use. Any effects of established pasture species on water quality can largely be attributed to the density and uniformity of the final stand; all pasture species that are adapted to the environment and management will have beneficial effects on water quality and quantity.

### Carbon (C) Sequestration

Established grasslands have considerable potential for C sequestration. However, the actual sequestration achieved is more dependent on biomass management than on species selection (Skinner, 2008; Don et

al., 2009). Harvesting more frequently and removing most of the aboveground mass can reduce the potential for C sequestration because root growth is reduced (Skinner, 2008). The primary mechanism for C sequestration in harvested or grazed forages is root growth, or more specifically, the relative rates of root growth and death/senescence (Frank et al., 2004). Senescent leaves and stems on the soil surface can be incorporated into the soil by microbial activity, however that process is slower than for ingestion and movement by earthworms.

Pasture species with high root mass, especially mass that is distributed deeper in the soil profile, have the potential for high rates of C sequestration. In switchgrass, for example, roots can account for 27% of total plant C, and plant crown material that is below ground can account for an additional 57% of plant C (Frank et al., 2004). Not only can the individual species affect root growth, the number of species may also be important. Skinner et al. (2006) found an 11-species pasture mixture had 30–62% greater root biomass than two- or three-species mixtures, and a greater proportion of roots were deeper in the soil. Even with this initial variation in root biomass however, their study did not find any differences in C sequestration among species mixtures after 4 yr.

Monocultures of six cool-season grasses and one warm-season grass averaged 60% more root mass than either alfalfa or red clover 2 yr after establishment (Bolinder et al., 2002). It was subsequently found that legumes allocated 43% of total carbon to roots and soil while grasses allocated 56% (Bolinder et al., 2007). Mixtures of legumes and grasses can have up to 73% of their C allocated to roots and soil (Bolinder et al., 2007). It can be concluded that species and cultivars that are productive and persistent will have better C sequestration potential than species that perform poorly, and mixtures are superior to monocultures.

### Species for Biofuel or Energy Production

Many grassland species have been evaluated for biofuel or energy production, including, for example, prairie cordgrass, sugarcane hybrids, sorghum, barley, Canada wildrye, big bluestem, indiangrass, sideoats grama, and alfalfa



...effects of pasture species on water quality are negligible compared to the effects of pasture cover”



Certified seed  
of named  
cultivars is highly  
recommended”

(Boukerrou and Rasmusson, 1990; Vogel et al., 2006; Boe and Lee, 2007; Dhugga, 2007; Lamb et al., 2007; Wang et al., 2008; Mangan et al., 2011). Although most grassland species have the potential for dual use as livestock forage and biofuel/energy, the contrasting requirements of these industries makes it likely that specialist species and/or cultivars will be necessary. In recent years, greatest interest has focused on switchgrass for biofuel/energy in much of eastern USA and the midwest (Vogel et al., 2002; Frank et al., 2004; Berdahl et al., 2005; Cassida et al., 2005; Mulkey et al., 2006; Boe and Lee, 2007; Vogel and Mitchell, 2008), however, miscanthus, giant reed (Clifton-Brown et al., 2001; Decruyenaere and Holt, 2001, 2005) and energy cane (Prine and French, 1999) also have high potential for biofuel/energy crops, but would be lower in dual-use potentials.

Plant breeders have found variation in the characteristics of many species proposed for use as biofuel/energy crops, and cultivars of some species are available in some regions (Berdahl et al., 2005; Boe and Lee, 2007; Murray et al., 2008; Wang et al., 2008). Typically, these cultivars have high yield potential, low fiber digestibility, low nutrient content, and consequently low ash content. To date, no genetically modified crop dedicated to biofuel/energy production is available; however, new information on the biochemical pathways suggests that scope for genetically modified cultivars is possible (Sticklen, 2007).

We found no published research evaluating effects of biofuel species on erosion, water runoff, or wildlife benefits during the establishment period. But recognizing the duration for establishment is relatively long, the risk would seemingly be rather high. This is an area needing research attention.

### Cultivars

Selecting appropriate cultivars of a species can be as important as selection of species for optimum grassland performance. For example, one cultivar of annual ryegrass resulted in more severe suppression of a new alfalfa stand than other cultivars, when used as a cover crop during establishment (Sulc and Albrecht, 1996). Although intended as a companion crop to provide soil protection and weed competition

during alfalfa establishment, the more vigorous annual ryegrass cultivars impaired growth of the developing alfalfa stand. Certified seed of named cultivars is highly recommended rather than variety not stated (VNS) seed. Several years of testing with red clover in Kentucky found only about 10% of seed lots of common red clover were as productive as certified seed (Olson et al., 2010).

Cultivars vary in many traits, and alfalfa cultivars, for example, show large variation that includes differences in insect and disease resistance, fall dormancy, winter hardiness, flowering date, and yield potential. Genetically modified alfalfa cultivars with genes for glyphosate (chemical and trade names are in Appendix IV) tolerance were first released in 2005. These were withdrawn from commercial sale in March 2007 while their environmental impact was investigated by USDA and again approved. Seed became nonregulated and commercially available again in January 2011. This glyphosate-tolerant technology will allow producers to better control weed competition during establishment (Hall et al., 2010). Once a weed-free stand is achieved, a well-managed alfalfa stand is relatively resistant to weed invasion.

Grazing tolerant alfalfa cultivars have belowground crowns and multiple stems per plant, resulting in improved persistence under grazing (Bouton and Gates, 2003). Similarly, white clover cultivars can show extreme variation in morphology, with large-leaved and erect types (e.g., ladino white clover) being better suited to hay production, and intermediate types (e.g., ‘Durana’) being better suited to grazing. The very-small-leaved prostrate types of white clover (e.g., Dutch clover) have low production and are unsuitable for most purposes. In contrast to their agronomic characteristics, most cultivars within a species have similar emergence characteristics, and differences in establishment are more likely caused by variation in seed quality than emergence rate per se.

Turf cultivars should never be confused or mixed with forage cultivars. In most cases, the yield potential of turf cultivars is much lower, tillering rates are higher, and leaf growth rates slower than those of forage cultivars.

Recommended seeding rates for turf cultivars are typically much higher than those for forage use. This is due to the need for more rapid and more uniform establishment in amenity areas than is necessary in forage stands, rather than any difference in the rates of emergence and establishment. Seed of turf cultivars of tall fescue and perennial ryegrass will likely be infected with an endophytic fungus that improves persistence of these species, but produces alkaloids that can be toxic to livestock and wildlife.

Many forage species are sold commercially as blends. For example, BG34® perennial ryegrass, StarGrazer® tall fescue, and Haymate® orchardgrass are sold as mixtures of several cultivars of their respective species. Although there may be benefits from genetic diversity in seeding mixtures of cultivars, this has rarely been addressed in the literature. The success of these blends can be attributed to both the component cultivars and the proportions of each that survive after

establishment. Biochemical and molecular methods can document the establishment of an improved cultivar seeded into a stand where a “naturalized” population of the same species already exists (Hopkins et al., 2000). Invariably, improved cultivars do not contribute significantly to the resultant stand unless significant changes to stand management (e.g., increased fertilizer use) are made.

Producers may prefer ‘tried and true’ cultivars over newer and often more expensive cultivars. Producers might successfully use a specific cultivar for specific conditions on their farm, but it may not be suitable for a nearby farm if grazing systems or hay management and fertilizer practices differ between the farms. In many cases cultivar selection depends on what is available at a local seed merchant.

The literature does not always support the superiority of improved cultivars over common or VNS seed of forage rye (McCormick et al., 2006), especially during establishment and

Birdsfoot trefoil 2 wk after spring broadcast seeding in Utah (compare to photo after spring planting). Credit: Jennifer MacAdam, Utah State University.



even later if the management does not use the superior feature. It should be noted that VNS seed could be an older cultivar or a new cultivar that does not have normal proprietary protections and guarantees. In another study, Lamb et al. (2006) found that older alfalfa cultivars had production similar to newer ones, except in more stressed environments and especially when persistence was challenged. Newer alfalfa cultivars had better persistence and productions in year 3 and thereafter (Lamb et al., 2006). Although, in general, cultivars of various grassland species showed very little difference in emergence rates, rates of germination and field establishment could be improved in bahiagrass by standard breeding methods (Anderson et al., 2009).

### Species Mixtures

Another consideration to be made before planting is whether a single or multiple species stand is desired. Many new seedings comprise

only 1 or 2 species, yet there are some benefits from establishment of biodiverse mixtures containing as many as 10 to 20 species (Sanderson et al., 2004, 2005). The literature is not clear on the benefits from complex mixtures, with results depending on the actual species used in the mixtures. Arguments against species-rich mixtures are the greater probability that one or more desired species are poorly adapted to co-establishment or specific environmental conditions, the greater management complexity of the resultant stand, and the unpredictability of the final botanical composition. There is some evidence that established grasslands may benefit from species-rich mixtures, especially on sites with highly diverse microenvironments such as mixed soil types, variable topography and soil fertility, patch grazing by livestock, and those subject to wide variations in weather that add stresses such as temperature, drought and flooding (Sanderson et al., 2002).

Spring-seeded birdsfoot trefoil  
10 mo after planting in Utah  
(drill rows run top to bottom)  
(compare to photo after spring  
planting). Credit: Jennifer Mac-  
Adam, Utah State University.



### Conclusion—Selection of Species and Cultivars

Code 512 emphasizes the selection of species and cultivars that are adapted to the site being planted. The characteristics to consider include climatic conditions; soil condition; landscape position; and any phytotoxic compounds, diseases, and insects that might be prevalent. The Code 512 Criteria place little emphasis on environmental or wildlife factors, but these were also included in this review because of their emerging interest. Changing climate, as evidenced by revision of the USDA Plant Hardiness Zone map in 2005 and 2012, may allow species that had once been considered unsuitable, to be suitable for some regions. This literature summary included 162 species (70 legumes, 79 grasses, and 13 forbs); however, just 28 of these species accounted for more than 50% of the research evaluated. The remaining species have potential for use in innumerable specialized situations and purposes, and additional research is warranted to explore these situations.

Selection of species and cultivars should also include the proposed use and management of the established stand. Some species and cultivars are better suited for grazing, and even within this designation, certain plant species are better suited than others for a particular animal species. Some species and cultivars are better used for hay or silage, and some are better used as biofuel/energy sources. Although it is desirable for grasslands to have multiple uses, the species and cultivars best suited for particular purposes generally do not have multiple-use options, e.g., the best alfalfa cultivars for hay production are likely poorly suited for grazing or biofuel use. Regrettably, characteristics that determine the suitability of a species for a particular use are not always associated with ease of establishment, and some desirable species can be difficult to establish.

The Code 512 Criteria emphasize that forage should meet the level of desired nutrition for the class of livestock. Forage species vary in their nutritional characteristics (e.g., digestibility, energy content, and protein content), and high-quality forages are essential for growing and lactating livestock (not so for mature and “dry” animals). The Code 512 Criteria also emphasize components of the

forage mixture should have similar palatability; however, research shows this specification is often unrealistic or infeasible. Grasses and legumes are frequently mixed in pastures to achieve an optimal combination of herbage production through the entire season, plus benefiting from biological nitrogen fixation. Competitiveness of a species in a mixture is related more closely to production of herbage than to the quality or palatability of the herbage. This characteristic is likely the most critical for establishment success making the species selection of the mixture restricted to matching those that are similar in competitiveness. Selective grazing due to different palatability is an inevitable feature of grazing mixed species that can be managed with rotational stocking (Chapter 3).

The Code 512 Criteria specify that species should be used that help meet livestock forage demand during times when normal production is inadequate. This specification is supported by the literature and deferred grazing (Chapter 3) or harvest of forage species suitable for hay or silage production may be required (Chapter 4). Selecting the species to establish for these purposes is important in the planning phase, and the establishment time or method may need to be altered to accomplish this goal. To date there is insufficient research on how each species provides the nutritional and environmental requirements of wildlife to make detailed species selections.

Another Code 512 Criteria is that species established for biofuel or energy production should provide the kinds and amount of plant materials needed for that purpose. This is supported by research, because some grass species are more suitable than others for cocombustion, cellulolytic fermentation, or other biofuel or bioindustrial application. Most research is based on use of perennials in monocultures that are harvested one or two times annually and are based mainly on biomass production and quality. Effects on the environment or wildlife remain unknown.

Code 512 Considerations specify establishing persistent species that can tolerate close grazing and trampling in areas where animals congregate, and where C sequestration is a goal, deep-rooted perennial species should



...the species and cultivars best suited for particular purposes generally do not have multiple-use options”

**TABLE 2.2.** Legume species and their recommended commercial rhizobia species and current sources of commercial strains.

Common name	Rhizobium species	Source and name of commercial strain
Alfalfa	<i>Sinorhizobium/Ensifer meliloti</i>	Nitragin A, <sup>1</sup> Dormal alfalfa, <sup>2</sup> N-Dure or Pre-vail alfalfa <sup>3</sup>
Bundleflower	<i>Rhizobium</i> spp.	CB 3126 <sup>4</sup>
Clover, alsike	<i>Rhizobium leguminosarum</i> bv. <i>trifolii</i>	Nitragin B, <sup>1</sup> Dormal-true clover, <sup>2</sup> N-Dure true clover <sup>3</sup>
Clover, arrowleaf	<i>Rhizobium leguminosarum</i> bv. <i>trifolii</i>	USDA 2298, <sup>4</sup> Nitragin R/WR/O <sup>1</sup>
Clover, ball	<i>Rhizobium leguminosarum</i> bv. <i>trifolii</i>	Identical to alsike clover
Clover, crimson	<i>Rhizobium leguminosarum</i> bv. <i>trifolii</i>	Nitragin R/WR/O, <sup>1</sup> Dormal true clover <sup>2</sup>
Clover, red	<i>Rhizobium leguminosarum</i> bv. <i>trifolii</i>	Identical to alsike clover
Clover, kura	<i>Rhizobium leguminosarum</i> bv. <i>trifolii</i>	USDA 2126 <sup>4</sup>
Clover, rose	<i>Rhizobium leguminosarum</i> bv. <i>trifolii</i>	WSM 1325, <sup>4</sup> Nitragin R/WR/O <sup>1</sup>
Clover, subterranean	<i>Rhizobium leguminosarum</i> bv. <i>trifolii</i>	USDA 2116, <sup>4</sup> Nitragin R/WR/O <sup>1</sup>
Clover, white	<i>Rhizobium leguminosarum</i> bv. <i>trifolii</i>	Identical to alsike clover
Cowpea	<i>Bradyrhizobium</i> spp. 'vigna'	Nitragin EL, <sup>1</sup> Royal Peat-cowpea <sup>2</sup>
Crownvetch	<i>Mesorhizobium</i> spp.	CrV-1 <sup>4</sup>
Deervetch	<i>Rhizobium leguminosarum</i> bv. <i>viciae</i>	DV-2 <sup>4</sup>
Lablab	<i>Bradyrhizobium</i> spp. 'lablab'	USDA 3605 <sup>4</sup>
Lespedeza	<i>Bradyrhizobium</i> spp. 'lespedeza'	Nitragin EL, <sup>1</sup> Royal Peat-cowpea <sup>2</sup>
Medic, barrel	<i>Sinorhizobium/Ensifer medicae</i>	WSM 1115 <sup>4</sup>
Medic, black	<i>Sinorhizobium/Ensifer medicae</i>	WSM 1115 <sup>4</sup>
Medic, burr	<i>Sinorhizobium/Ensifer medicae</i>	WSM 1115 <sup>4</sup>
Medic, little burr	<i>Sinorhizobium/Ensifer medicae</i>	WSM 1115 <sup>4</sup>
Medic, rigid	<i>Sinorhizobium/Ensifer medicae</i>	M 49 <sup>4</sup>
Medic, Tifton burr	<i>Sinorhizobium/Ensifer meliloti</i>	Nitragin A <sup>1</sup>
Milkvetch, cicer	<i>Rhizobium</i> spp.	USDA 3811 <sup>4</sup>
Mungbean	<i>Bradyrhizobium</i> sp. 'vigna'	Nitragin EL, <sup>1</sup> Royal Peat-cowpea <sup>2</sup>
Prairie clover	<i>Rhizobium</i> spp.	USDA 3742 <sup>4</sup>
Sainfoin	<i>Rhizobium</i> spp.	Sain-1 <sup>4</sup>
Sulla	<i>Rhizobium</i> spp.	Hedy-2 <sup>4</sup>
Sweetclover	<i>Sinorhizobium/Ensifer meliloti</i>	Identical to alfalfa
Tickclover	<i>Bradyrhizobium</i> spp.	CB 756 <sup>4</sup>
Trefoil, big	<i>Bradyrhizobium</i> spp. 'lotus'	USDA 3469 <sup>4</sup>
Trefoil, birdsfoot	<i>Rhizobium/Mesorhizobium loti</i>	Dormal-trefoil, <sup>2</sup> Pre-vail trefoil, <sup>3</sup> BFT-1 <sup>4</sup>
Vetches	<i>Rhizobium leguminosarum</i> bv. <i>viciae</i>	Nitragin C, <sup>1</sup> Nodulator, <sup>2</sup> N-charge, <sup>3</sup> V-1 <sup>4</sup>

<sup>1</sup>EMD Crop BioScience, 13100 West Lisbon Avenue, Suite 600, Brookfield, WI 53005. <http://www.nitragin.com/homepage>. <sup>2</sup>BeckerUnderwood, 801 Dayton Avenue, Ames, IA 50010. <http://www.beckerunderwood.com>. <sup>3</sup>INTX Microbials, 200 West Seymour, Kentland, IN 47951. <http://www.intxmicrobials.com>. <sup>4</sup>Plant Probotics, 6835 Lindel Court, Indianapolis, IN 46268. [tomwacek@yahoo.com](mailto:tomwacek@yahoo.com).

be selected that will increase underground C storage. Research shows there is variation among species and cultivars in tolerance of trampling and close defoliation, and in the extent of root growth. However, there are also limitations in the extent to which grasslands species can express these traits in these harsh conditions, and management such as delaying defoliation and fertilizer use, can be

as important as species selection in achieving those goals (Chapters 3–5).

Overall, it is clear that the choice of which species to establish is more dependent on the ultimate use of the stand than on the ease of establishment. Most grasslands are planted with perennial species intended for long-term use, e.g., hay or silage production, a riparian area

or a grazing pasture, so the choice of species should be made carefully. Although there is usually a single predominant purpose, there are invariably other benefits and ecosystem services that are associated with grassland, and in most cases the landowner prefers to select species for their versatility in different situations. Flexibility allows the landowner to alter the use or apply adaptive management to correct problems such as using a pasture for hay in spring to control some weeds or grazing the pasture during fall to weaken the grass stand to plant a legume the following spring. But the adaptive management also depends on recognition of the problem and knowing the best ways to ameliorate the problem.

### IMPORTANCE OF LEGUME INOCULATION

The presence of functioning nodules from the genera *Rhizobium*, *Bradyrhizobium*, *Mesorhizobium*, *Sinorhizobium*, or *Azorhizobium* on legume roots is critical for N fixation. In addition to the number of nodules per plant, the activity of these nodules combines to determine the rate of N fixation. There are unique rhizobia species for each legume species; however, some rhizobia species can infect several host–legume species. In general, where a legume species has not previously been planted, it is imperative to ensure that seed is rhizobia-coated prior to seeding. Where the given legume has previously been planted, there are usually sufficient naturalized rhizobia populations to ensure infection occurs; however the N-fixation rate for these populations can be considerably lower than for introduced strains that are available commercially.

Rhizobia are generally host specific and, therefore, selecting the correct strain for each legume species is critical for growing legumes that can fix atmospheric N. Red, white, ball, and alsike clovers can use the same rhizobia strain; however, arrowleaf, kura, rose, and subterranean clovers each require a unique strain. During years with high costs of N fertilizer, this advantage seems obvious; however, research in this field is on the decline (Brockwell and Bottomly, 1995). The inoculants and strains that are recommended for each legume species are summarized in

Table 2.2. Because of the dependence on commercial production and marketing, it is becoming difficult to find commercial quantities of rhizobia inoculants for the less commonly used legumes, and generally inoculants for only alfalfa, white clover, and red clover are approved for organic use by the Organic Material Review Institute (OMRI).

There are several difficulties in summarizing the literature related to rhizobia strains and giving recommendations for their use. Many studies (e.g., Jones et al., 1978; Prévost et al., 1987; Coll et al., 1989; Trotman and Weaver, 1995) report on strains collected locally, but not available commercially. In other cases a commercial inoculant might be listed in a research publication, but the specific strain(s) used is not reported or even known. The authors are aware of only four commercial companies in the USA that produce and sell inoculants for a broad range of forage legumes (Tables 2.2 and 2.3), and the specific strains in the product are usually not listed. References relating to rhizobia strain selection, evaluation, and the best treatment found in each respective study are summarized in Table 2.3. However, these strains are often not those commercially produced, which shows some disconnect between research and ultimate commercialization.

Rhizobia infection (i.e., the number of nodules) and the rate of N fixation (includes activity nodule<sup>-1</sup>) are sensitive to biotic and abiotic stresses. Generally any stress that reduces photosynthesis or plant growth will reduce infection and subsequent N fixation. Drought, heat, desiccation, soil acidity, salinity, nutrient deficiencies, some pesticides, and residual N in the soil have been identified as major factors limiting rhizobia populations and their formation of nodules (Thies et al., 1991; Zahran, 1999).

Literature relating rhizobia to management and technologies, such as adhesives, pelleting, and cropping history is summarized in Table 2.4. Rhizobia must adhere to the seed to ensure the desired bacteria are near the seed when it germinates. The roots release chemical signals to the bacteria that lead them to infection of the root and subsequently effective nodulation. One study found that water alone was



There are unique rhizobia species for each legume species”

**TABLE 2.3.** Rhizobia–legume references related to comparing optimum strains.

Legume species	Rhizobium species	Comparison	Best strain or inoculant	Reference
Alfalfa	<i>Sinorhizobium melilotii</i>	2 strains; 2 CO <sub>2</sub> levels	A2 > NRG34	Bertrand et al. (2007)
Alfalfa	<i>S. melilotii</i>	2 strains	WSM419	Cheng et al. (2002)
Alfalfa	<i>S. melilotii</i>	4 parent/mutants	102F51, 102F34	Hardarson et al. (1981)
Alfalfa	<i>S. melilotii</i>	26 strains	WSM 826	Howieson et al. (2000)
Alfalfa	<i>Rhizobium leguminosarum</i>	3 strains	NS	Stout et al. (1997)
Alfalfa	<i>S. melilotii</i>	17 strains	CCBAU3013	Zeng et al. (2007)
Arrowleaf clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	16 strains; 3 pH	N fertilizer > 6A,6B,6C,9A,9B	Coll et al. (1989)
Arrowleaf clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	160 strains	W8-1, W9-4, W9-6 local strains	Trotman and Weaver (1995)
Arrowleaf clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	18 strains	Not identified	Trotman and Weaver (2000)
Cicer milkvetch	<i>R. leguminosarum</i> , <i>S. melilotii</i>	13 strains	B2 and 9462L	Zhao et al. (1997)
Cowpea	<i>R. leguminosarum</i> bv. <i>phaseoli</i>	3 strains; 2 carriers	Oil-based > peat-based inocula; 971A	Kremer and Peterson (1983)
Crimson clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	5 strains	K13, X95	Smith et al. (1982)
Faba bean	<i>R. leguminosarum</i> bv. <i>viciae</i>	67 strains	Strains effective on vetch and peas	Van Berkum et al. (1995)
Kura clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	18 strains	N fertilizer	Beauregard et al. (2003)
Kura clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	27 strains	3D1Y8, 3D1Y8(b)	Erdman and Means (1956)
Kura clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	+/- 1 strain	None	Seguin et al. (2001)
Mung bean	<i>Bradyrhizobium</i> spp.	40 strains	Eight effective on acid soils	Munns et al. (1979)
Sainfoin	Not reported	31 strains	Five experimentals = SM2 and 116A15	Prévost et al. (1987)
Subterranean clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	10 strains	NS (IST51, IST54 IST65, USDA 2156)	Rumbaugh et al. (1990)
Subterranean clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	33 strains	18 strains NS	Thornton and Davey (1983)
Subterranean clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	9 strains	X16, X47	Jones et al. (1978)

ineffective as a sticking agent for peat-based inoculant, but that gum arabic was an effective adhesive for ensuring nodule formation on white clover at both low and high levels of inoculation (i.e., 600 and 3000 rhizobia seed<sup>-1</sup>, respectively; Waggoner et al., 1979). Formulations such as peat or pelleting, which provide physical protection to the rhizobia, or management techniques such as planting

deeper to moisture should enhance nodulation (Walley et al., 2004). Nodulation was similar between liquid inoculum and peat-based inoculum for field pea (Hynes et al., 1995), but the liquid formulation was much easier to apply.

Under dry soil conditions, peat-based and granular formulations resulted in more

nodules on field pea compared to a liquid formulation (Walley et al., 2004), which was attributed to physical protection of the rhizobia from heat and desiccation. Surface seeding was detrimental to rhizobia under dry conditions and planting at 16-mm depth optimized rhizobia survival, seedling emergence, and survival of arrowleaf clover (Rich et al., 1983). Exposure of rhizobia to 5 hr or more of sunlight or 2 wk in dry soil without germinating resulted in less effective inoculation (Alexander and Chamblee, 1965). Therefore, if seed are not preinoculated commercially, it should be inoculated effectively on the same day it is planted.

Contrary to Waggoner et al. (1979), seedling emergence and the resultant yield from lime-

pelleted seed of red clover, white clover, and alfalfa did not differ from seed inoculated with rhizobia using water as the sticker agent (Olsen and Elkins, 1977). Similarly, lime pelleting containing rhizobia did not improve subterranean clover yield in the seeding year when compared to nonpelleted seed treated with a commercial inoculum on three of four soils (Williams and Kay, 1959). However, lime pelleting seed increased yield of arrowleaf clover in a nonfumigated soil over an otherwise equivalent fumigated soil, suggesting that pelleting assisted introduced rhizobia to compete with native soil microorganisms (Wade et al., 1972).

Encapsulating rhizobia into a seed coating helps protect the bacteria from environmental

**TABLE 2.4.** Summary of rhizobia responses to management and coating treatments.

Legume species	Rhizobium species (if stated)	Comparison	Best treatment	References
Alfalfa		Desiccation; sunlight	< 3 hr sunlight; < 2 wk desiccation	Alexander and Chamblee (1965)
Alfalfa		Two stickers	Lime pelleting = water	Olsen and Elkins (1977)
Alfalfa		+/- pelleting	Pelleting > nonpelleted	Vincent and Smith (1982)
Annual medics	<i>Sinorhizobium melilotii</i>	+/- N fertilizer; 1 strain	102G3 and 102A13 greatest occupancy	Zhu et al. (1998)
Arrowleaf clover	<i>Rhizobium leguminosarum</i> bv. <i>trifolii</i>	Two stickers	Pelgel gum arabic > water sticker	Rich et al. (1983)
Arrowleaf clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	+/- pelleting; rates	Lime pelleting = fumigation	Wade et al. (1972)
Hairy vetch		Cropping history	Inoculation beneficial 50% of time	Andrews (1940)
Lespedeza		Three timings; 3 N rates	Starter N increased growth; no effect of timing	Bender et al. (1988)
Pea	<i>R. leguminosarum</i> bv. <i>viciae</i>	Two formulations	Liquid = peat carrier; 128C56G strain	Hynes et al. (1995)
Pea		Cropping history	Inoculation beneficial 33–50% of time	Vessey (2004)
Red clover		Two stickers	Lime pelleting = water	Olsen and Elkins (1977)
Red clover		+/- pelleting	No differences	Vincent and Smith (1982)
Subterranean clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	13 coatings/ adhesives	Peat > broth; gum arabic > pelleting	Radcliffe et al. (1967)
Subterranean clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	Lime pelleting or band	Limestone band pH 4.6; NS other sites	Williams and Kay (1959)
White clover	<i>R. leguminosarum</i> bv. <i>trifolii</i>	Two stickers	Gum arabic adhesive > water	Waggoner et al. (1979)
White clover		Two stickers	Lime pelleting = water	Olsen and Elkins (1977)

stress. The literature is inconsistent on whether coating is beneficial for maintaining rhizobia viability or enhancing seedling vigor.

Competition between introduced and native strains of rhizobia can be one reason for inoculation failures (Thies et al., 1991). In Hawaii, on sites with moderate background populations of native rhizobia as low as 50 rhizobia g soil<sup>-1</sup>, seed inoculated with rhizobia frequently showed no increase in yield. With a low background population of <10 indigenous rhizobia g soil<sup>-1</sup>, however, rhizobia inoculation increased economic yield of several legumes 85% of the time (Thies et al., 1991). Pellet-coating seed increased the number of nodules plant<sup>-1</sup>, N content, and seedling growth of alfalfa, whereas pelleting did not improve nodule formation on red clover (Vincent and Smith, 1982).

It is a good practice to inoculate legumes each time they are planted, even when the same

legume has been grown recently on the same field. Andrews (1940) tested noninoculated seed of vetch on 77 soils that had previously grown vetch. Half had a lower yield than those where seed had been treated with commercial inoculant. Vessey (2004) also reported positive alfalfa yield responses 33–50% of the time when inoculated seed was planted in fields with a prior alfalfa cropping history. Thus, inoculation of the seed just prior to planting is generally considered good insurance when planting legume seed, because of the more rapid growth rate of seedlings and better seedling vigor that usually occurs during establishment (Vincent and Smith, 1982).

### Conclusion—Type of Legume Inoculant Used

General Criteria of Code 512 specify that legume seed should be preinoculated or inoculated with the proper viable strain of rhizobia immediately before planting, which

Cicer milkvetch 10 mo after spring planting in Utah (compare to birdsfoot trefoil 10 mo after planting). Credit: Jennifer MacAdam, Utah State University.



is supported by the literature. In addition, the literature supports making legumes self-sufficient for N supply in that legume seed inoculated with the proper rhizobia strain will improve establishment of forage and biomass crops by increasing seedling vigor, accelerating canopy closure, and ensuring earlier ground cover to reduce soil erosion and improve water quality. Properly inoculated legume seed will produce plants that are higher in protein than those from non-inoculated seed that can lead to improved nutrition and health of livestock and wildlife without the economic and environmental costs of N fertilization.

## SEED COATINGS AND PRETREATMENTS

Seed coatings are a broad group of compounds that can be applied to seed to modify their germination and establishment characteristics. The most common coatings include rhizobia (for legumes), lime, nutrients, insecticides, fungicides, nematicides, and their associated adhesives. Invariably, these products increase seed weight by as much as 100% and reduce the amount of pure live seed (PLS) applied (seed  $m^{-2}$ ) for a given seeding rate (g  $m^{-2}$ ). Seed pretreatments contrast from seed coatings by modifying the seed and its coat, but do not appreciably affect the seeding rate. Seed pretreatments include deawning to improve seed flow for mechanical planting, scarification to improve water imbibition, seed priming and preimbibition to enhance early germination and emergence, and chilling to reduce dormancy.

Seed coatings were first used in China around 100 BC, and comprised seed pellets made from a slurry of ground horse bones, herbal extracts, silkworm droppings, and sheep dung (Gong et al., 2003). The modern coating and treatment options have been reviewed by Scott (1989).

Many coatings and pretreatments have been investigated as aids to germination; however, evidence in the research literature is inconsistent about the benefits these provide. Although seed coatings generally provide benefits to seedling emergence and protect the seed from adverse environmental impacts, in some situations the very nature of the coating can be a barrier to the environment and slow or delay germination. Generally, the benefits of

coatings may be more evident when the seed and seedling are in a stressful environment.

The choice to use seed coating is affected more by the nature of the species than by the intended purpose for the grassland planting. Seed coatings used to enhance germination and the success of establishment can benefit all purposes. We found and summarized 15 publications that investigated seed coatings and treatments within a forage production context, but none investigated seed coatings and treatments for ecosystem benefits, specifically for soil or water conservation, environmental protection, wildlife, or C sequestration.

### Seed Coatings

Lime coatings are the most common and can protect rhizobia viability during storage and benefit establishment indirectly through improved nodulation and subsequent N fixation. Most rhizobia carriers used in alfalfa seed coating add 10–30% to the seed weight. With spring-planted alfalfa in Minnesota at 16.8 kg PLS  $ha^{-1}$ , a lime-based seed treatment (RhizoCote®) increased the stand density by an average of 31% over the control in 5 of 14 field studies, with no difference measured in the remaining studies. This advantage was increased to 54% for 8 of 14 studies when metalaxyl, a fungicide, was also used in the coating. In 10 of these studies, yield the seeding year was increased by an average of 6.6% from the lime coat used in conjunction with a fungicide or pesticide (Sheaffer et al., 1988). This study also compared bare and coated alfalfa seed at the same seeding rate (16.8 kg  $ha^{-1}$ ), which, in effect, added 34% weight seed $^{-1}$  because the coat reduced specific seed weight from 485 to 320 seeds  $g^{-1}$ . In this case, although the lower seeding rate was partially offset by greater seed emergence for the coated seed, the final stand density was reduced in only one of four studies. However, if fungicide or pesticide was added to the coating, the final stand density at the low rate was not statistically different from the control.

Lime coatings may have other less direct effects on seedling emergence by modification of seed texture. In the case of rough and/or fluffy seed, lime coatings can improve their flow through a seeder. In the case of aerial seedings, lime coating can increase seed weight (especially for



...legume seed inoculated with the proper rhizobia strain will improve establishment of forage and biomass crops”



Factors most often related to seed vigor are seed size or weight, duration of seed storage, and the seed storage environment.”

light seed such as orchardgrass) and contribute to a successful seeding by enhancing seed ballistics and ensuring seed actually hits the target area, and lands with greater force to improve seed to soil contact (Scott, 1989; Loch, 1993).

Many studies describe where fungicides, insecticides, and nematicides have been included in seed coatings. Having the chemical products near the germinating seed might give greatest protection. Greater benefit arose from use of fungicides as seed coats, but benefits also occurred for insecticides and nematicides where these pests were present (Sheaffer et al., 1988). In New Zealand, laboratory and field studies with white clover found seed coating containing the insecticides carbosulfan and isofenphos improved early seedling establishment when a native weevil was present, and a commercially available white clover seed treated with the insecticide, furathiocarb, increased seedling survival and yield for up to 13 mo after sowing (Barratt et al., 1995). In this study, carbosulfan caused rapid mortality of rhizobia, whereas isofenphos and furathiocarb caused no significant mortality of rhizobia (Barratt et al., 1995). Studies in New Zealand found no benefit to final stand for seed-coat applications of carbofuran or furathiocarb insecticides for no-till perennial ryegrass (Barker et al., 1990).

Of concern is the potential effect of insecticide use on nontarget organisms. In one French study, the effect of an insecticide (imidacloprid) seed coating on sunflower was investigated on subsequent nontarget pollinator populations of bumblebee (Tasei et al., 2001). When used at the registered dose in the greenhouse or field, there were no significant effects on bumblebee foraging and homing behavior, or on colony development.

Nutrients attached to the seed as a coating offer potential for early nutrition of the emerging seedling, but may raise the risk of incurring damage from the high osmotic potential of such solutes. The nutrient most likely to be of benefit is phosphorus (P). In Norway, P seed coatings of oat enhanced biomass accumulation up to 22% and grain set up to 15%, but had no benefit for grain yield (Peltonen-Sainio et al., 2006).

### Seed Pretreatment

Hard seed is a common condition of natural plant populations, in which dormancy can be caused by an impermeable seed coat (Ghersa et al., 1997). The most common pretreatment in this case is scarification of the seed coat by physical abrasion or chemical weakening to allow easier movement of water or oxygen into the seed. Mild physical abrasion with sandpaper increased germination of white clover from about 3% to 70% (Burton, 1940). For cicer milkvetch, the best scarification treatment among 30 different time, pressure, and abrasion combinations reduced the percentage of hard seed from 54% to 1% (Townsend and McGinnies, 1972b). Most responses to scarification have been observed for legumes and other dicotyledonous species, but also are effective for some warm-season grasses, such as eastern gamagrass (Tian et al., 2002).

Many seed pods, seed coats, and seed integuments contain germination inhibitors that can delay the germination of seed under natural conditions (Carleton et al., 1968). Frequently, these compounds are leached by water, allowing the seed to germinate and establish after sufficient time to leach and once appropriate temperature and moisture conditions occur. Most commercial seed has these pods and husks removed to ensure more rapid and uniform seed germination. For farm-saved seed of forage species such as sainfoin, the failure to remove seed pods and husks may result in poorer germination and establishment.

Several forage seed species (e.g., switchgrass, eastern gamagrass) have a period of dormancy immediately following harvest (Madakadze et al., 2000; Rogis et al., 2004). This is a natural mechanism to prevent premature germination of seed under field conditions until exposed to a period of cold such as winter. The most common treatment to reduce or shorten this dormancy is a period of cold treatment following imbibition (stratification) with water that mimics overwintering in the soil. Some studies have found improved germination following several weeks of stratification at 5°C, or several cycles of alternating cool and warm temperature, depending on species. If needed, most commercial seed has already been scarified and should not require additional treatment. Farm-saved seed may require artificial

stratification if the seed is not planted in the autumn to stratify naturally.

Various seed-priming methods have been used experimentally to increase seed germination rate (Rao et al., 1987; Artola et al., 2003a). In these cases, the seed is allowed to imbibe water and begin to germinate for several hours, but then is redried. When water is added again the seed germinates and begins seedling growth very quickly. For example, field and laboratory studies have found germination of Lehmann lovegrass seeds can be improved by various presowing seed treatments such as alternate moistening and drying, oven-drying, scarification, and prechilling on a moist substrate (Haferkamp et al., 1977). The increased germination may be due to improved seed-coat permeability or to a change in the metabolic state of the seed (Haferkamp et al., 1977). In contrast, surface-sowed primed seed of white clover, orchardgrass, and perennial ryegrass had rapid early emergence; however, unfavorable rainfall during later seedling growth resulted in lower overall emergence (Barker and Zhang, 1988). The emergence of big bluestem and switchgrass was increased 18% by seed priming treatments in greenhouse studies, but had no benefit in field studies (Beckman et al., 1993).

### Conclusions—Seed Coatings and Pretreatments

The Code 512 General Criteria specify that seeding rates be calculated on a PLS basis, suggesting seeding rates of coated seed based on weight need to be adjusted upward. The literature suggests that benefits of seed coating may partially offset the lower seeding rate on a weight basis. There is also an economic consideration, because coated seed is usually more expensive to purchase, so the recommendation for a higher seeding rate to achieve constant PLS adds significantly to the cost of a seeding. Seedlings with a short-term financial return (e.g., hay, grazing, or biomass) may benefit from the use of more expensive coated and pretreated seed, whereas seedlings without short-term financial return such as those for conservation and wildlife may not justify the additional seed cost.

New technology is likely to improve the performance of seed coatings. New adhesives,

pesticides, and products such as inert carriers, are likely to improve efficacy of seed coating. For example, polymer seed coatings are being used for corn and canola, and in the future may become cost effective for high-value forage crops such as alfalfa. Polymer coatings such as polyvinylidene chloride, ethyl cellulose, and polyvinyl acetate polymer resin have been evaluated for protecting seed from insects and diseases, and preventing water absorption while in storage (TeKrony, 2006). Most polymer coatings are very thin (1–10% of seed weight) and do not add appreciably to seed weight (TeKrony, 2006). Thickness is critical, because a coating rate of one or two layers of polyvinyl acetate polymer increased rate of seed water uptake, whereas five layers of coating slowed rate of water uptake.

### SEED SOURCE AND ANALYSIS

Seed certification provides a guarantee of genetic identity and cultivar purity, as well as minimizing content of restricted and prohibited noxious weed seeds. State seed laws further add limits on seed of prohibited weeds and noxious species. Standard seed testing also includes determining germination and hard seed percentages. Hard seed does not germinate quickly because of an impervious seed coat, but might germinate once the seed coat is

August seeded birdsfoot trefoil  
2 mo after planting with oat as  
a companion crop (cut). Credit:  
Jennifer MacAdam, Utah State  
University.





## Does seed that meets state quality standards improve establishment...?”

degraded. These criteria define the ability of seeds to germinate and develop into vigorous seedlings to hasten stand establishment. Higher-quality seed will usually be larger and have faster emergence, but seed size is not usually reported for commercial seed lots. This section addresses the two questions: Does seed that meets state quality standards improve establishment to have the planted seed become the dominant canopy type(s) with few weeds, and does it decrease the time for the planted seed to develop a usable canopy?

Most published research has documented seed-quality effects on emergence rates for stands established for production purposes such as hay, silage, or grazing. As a generalization, these factors should also have positive influences on stands where the purpose is for erosion control, wildlife, C sequestration, or biomass, although no literature was found on these latter issues.

Seed vigor comprises those properties that determine the potential for rapid, uniform emergence and development of normal seedlings under a wide range of field conditions (Baalbaki et al., 1983). It is most often tested by measuring germination of stressed seeds with the use of an accelerated aging test or a cold test. The cold test attempts to measure the combined effects of genotype, seed quality (both physical and physiological), seed or soil-borne pathogens and seed treatment. Other tests include rate of germination, rate of seedling growth, and tests of metabolic activity with the use of tetrazolium chloride, electrical conductivity, and respiration rates.

Factors most often related to seed vigor are seed size or weight (Heydecker and Coolbear, 1977), duration of seed storage, and the seed storage environment. Larger or younger seed often result in more rapid rates of establishment and early plant growth; however, rapid establishment should reduce risk of environmental outcomes, but does not always result in higher yield (TeKrony and Egli, 1991). Seed vigor can have a measurable effect on yield by way of improved stand establishment, which in turn is influenced by emergence and uniformity of overall establishment (TeKrony and Egli, 1991).

The electrical conductivity test and the

accelerated aging test were the most effective predictors of field emergence for legume species, whereas the standard germination test was the best predictor of seed vigor for grasses (Wang et al., 2004). In situations such as late or low-density plantings, or in plantings where weed competition is strong, rapid establishment can improve survival and competitiveness of desired species to make a significant contribution to yield.

Differences in seed size of alfalfa did not influence the number of seedlings that emerged, but large seed was positively related to seed vigor, measured as plant biomass (Beveridge and Wilsie, 1959). This occurred because seed reserves remaining after emergence can support more rapid accumulation of leaf area and photosynthesis capacity by the seedlings. In white clover, sown at the same PLS percentage, higher-quality seed (e.g., heavier seed with faster germination) resulted in higher yield and significantly lower weed content in the year following planting (Pasumarty et al., 1996). Similarly, in a growth room study, larger seed size of birdsfoot trefoil produced larger cotyledon area of emerged seedlings and greater seedling vigor (Shibles and MacDonald, 1962).

Whereas established plants of kura clover are very persistent, seed are small and seedling establishment is slow. Selection for improved seed vigor, based on earlier work with birdsfoot trefoil (Twamley, 1974), showed seedling fresh shoot weight was a better indicator of seedling vigor than was seed size (DeHaan et al., 2001; Artola et al., 2003b). DeHaan et al. (2001) found kura clover seed size was correlated with fresh shoot biomass, and that fresh shoot biomass at 42 d after planting was the best and most practical selection criterion to improve seedling vigor.

Seed storage conditions can alter seed vigor over time (Zarnstorff et al., 1994). Low temperature (0–2°C) and low relative humidity (6%) are recommended for long-term (20 yr) viability of seed. During a 10-yr study, white clover seed stored at 2°C and 10–20% humidity actually increased in germination percentage as the hard seed percentage decreased. When temperature and humidity were both controlled, storage container (i.e.,

cloth bag, glass jar, or resealable plastic bag) did not affect grass-seed vigor, measured as the rate of hypocotyl elongation following germination (Lewis et al., 1998). At 4°C and 70–90% humidity, vigor of grass seed was higher after 10 yr when seed was stored in cloth bags than in glass jars or plastic bags. When neither temperature nor humidity was controlled, grass seed stored in resealable plastic bags had the highest vigor after 10 yr (Lewis et al., 1998). The authors noted that although germination was similar for grass seed stored in low-temperature environments, seed vigor was significantly less when storage humidity was higher, regardless of storage container.

### Conclusion

The literature supported the Code 512 Criteria that all seed and planting materials should meet state quality standards. Noxious species cannot be planted for legal reasons. Based on the nine articles reviewed, the most important single measure of seed quality is the germination test and its date, as reported on the seed label. Although various other seed-quality characteristics can predict establishment, two useful characteristics, i.e., seed size and seed storage conditions, are not reported on seed labels. As a generalization, seed should be stored on-farm for the least possible time to minimize seed deterioration during storage; where on-farm storage is necessary seed should be stored in a cool dry location.

### FERTILIZER APPLICATION

Although nutrient management implications of fertilizer and lime are discussed in detail in Chapter 5, this section considers the specific effects of fertilizer and lime on grassland establishment. The application of N and P fertilizer at establishment can improve plant emergence and seedling vigor, especially when soils have low fertility. Fertilizer application at seeding is useful irrespective of whether the purpose of a seeding is for forage production or quality, for biofuel/energy, or for conservation purposes such as C sequestration, water quality, or erosion control. The benefits are likely to be achieved more quickly and with less risk with appropriate fertilizer and lime application.

Banded fertilizer application of N and P has considerable potential to reduce environmental

impact of a seeding, compared to the negative impacts that might result from a poor or failed stand (Teutsch et al., 2000). Banded fertilizer placement is only possible with coulter-type (no-till) drills, and is not possible for broadcast planters such as a cultipacker or Brillion® seeder. These nutrients, placed near the seed, but not in contact with it, increase the number of emerged plants, shorten their time to emergence, and increase effectiveness of these nutrients at low application rates (Kroth et al., 1976). Their study compared 48 combinations of N, P, and K in Missouri, and found that a fertilizer mixture of 17 kg N ha<sup>-1</sup> and 15 kg P ha<sup>-1</sup>, banded 2.5 cm below and 2.5 cm to the side of the seed, gave optimum establishment results for August and April seedings of reed canarygrass.

### Nitrogen

Fertilizer N has variable effects on seedling emergence. Of the six articles summarized, three reported inhibited legume emergence, one found no response, and two found improved legume establishment with N fertilization (West et al., 1980; Seguin et al., 2001). In Virginia, N fertilizer reduced the stands of alfalfa, white clover, red clover, and birdsfoot trefoil, whether sown alone or in mixture with orchardgrass (Ward and Blaser, 1961), which was attributed to salt damage of the young seedlings as N rate was increased. Stands, root length, root weight and root:shoot ratio of birdsfoot trefoil and the botanical composition of orchardgrass-birdsfoot trefoil swards were not significantly influenced by 28 kg N ha<sup>-1</sup> as starter fertilizer (Watson et al., 1968). In one Missouri study with three alfalfa cultivars over 3 yr, 45–95 kg N ha<sup>-1</sup> decreased the establishing population to 88% of unfertilized plots, but still had a positive yield response (Peters and Stritzke, 1970). Grass establishment is usually responsive to fertilizer N (Kroth et al., 1976).

The effect of N fertilizer at seeding also depends on the extent of weed control. In Missouri, alfalfa establishment in spring with appropriate weed control, adequate rainfall, and a fertile soil (pH 6.5, 110 kg P ha<sup>-1</sup> in soil) was improved with N at seeding in 2 out of the 3 yr studied (Peters and Stritzke, 1970). In the same study, but without chemical weed control, the alfalfa stand was reduced because



...benefits are likely to be achieved more quickly and with less risk with appropriate fertilizer and lime application”

of competition from weed growth where N was used.

With sod seeding in early spring, especially with incomplete kill of existing vegetation, there are some cases where N applications can reduce seedling emergence; presumably because of the greater competition from established vegetation that can smother the emerging seedlings. In Quebec, for example, N had variable effects on sod-seeded red, white, and kura clovers depending on the extent of control of the prior sward by herbicides (Laberge et al., 2005).

### Phosphorus

Four research papers were found that specifically addressed forage establishment and seedling emergence responses to P fertilizer application. In Ontario, seedling growth of alfalfa, birdsfoot trefoil, and smooth brome grass was increased up to five times by banding 30 kg P ha<sup>-1</sup> at 5 cm depth, prior to a surface seeding (Sheard, 1980). Growth and winter survival of an August seeding of reed canarygrass and the growth of an April seeding were stimulated by P in a low-fertility soil (Kroth et al., 1976). Pitman (2000) reported a linear yield response to P fertilizer up to 80 kg P ha<sup>-1</sup> for tall fescue during the establishment year in Louisiana. At four locations in Ohio, significantly greater

shoot and root dry weight occurred with spring-seeded alfalfa when P was banded at 27 kg P ha<sup>-1</sup>, with no significant difference in the plant population (Teutsch et al., 2000). The primary mechanism of the P response for grass and legume establishment was by promotion of root growth (Teutsch et al., 2000). Preferably, P should be soil-incorporated prior to seeding because it has low solubility (Doll et al., 1959).

In some specialized situations, such as the establishment of native grassland, low P may be a necessary prerequisite for the establishment of species-rich vegetation. In Europe, low soil P, < 5 mg 100 g<sup>-1</sup> of dry soil, was an “indispensable prerequisite” for increasing species diversity in agricultural grasslands because P promoted the growth of the more productive and competitive species (Peeters and Janssens, 1998).

### Potassium (K)

Three articles described K effects on seedling emergence; however, results were variable and showed an interaction with P. There was no effect of K on winter survival or growth of reed canarygrass from either August or April plantings (Kroth et al., 1976). Pitman (2000) found some K responses for tall fescue when seed were hand broadcast and incorporated by rotovator into a low-fertility soil of the Louisiana coastal plain, but responses were invariably better when P and K were used together. Similarly, in an earlier study with white clover at the same location, applying P and K fertilizer at seeding resulted in 12% more plants being established (Suman, 1954).

### Lime

A correct soil pH is required for optimal seedling establishment, because acid soils reduce forage establishment rates, especially for alfalfa and other legumes. Soil acidity impairs the process of nodulation and reduces the ability of legumes to fix N. Soil acidity also slows seedling root growth during establishment and reduces plant availability of many essential nutrients. Early in the history of alfalfa establishment, the need to treat acidic soils with lime was well documented (Albrecht and Poirot, 1930). In general, surface-applied lime takes several weeks to change the soil pH, and lime or dolomite applications should be made and incorporated several months prior to seeding, rather than during or after

August seeded birdsfoot trefoil, at 2 months after planting without oat (compare with photo with oat as companion crop). Credit: Jennifer MacAdam, Utah State University.



any seeding operation. Establishment of tall fescue in a low-pH soil (pH 4.9–5.8) was improved by lime applications at two of three Louisiana sites (Pitman, 2000). Lime seed coating was found to be ineffective in improving legume establishment into an acid (pH = 4.7) tall fescue pasture in Illinois (Olsen and Elkins, 1977). Presumably, insufficient lime accompanied the seeding, and the authors concluded a presowing lime treatment of the soil might have had more positive results.

### Sulfur (S)

In Saskatchewan, S was reported to have negligible influence on seedling emergence or survival of alfalfa, but did improve production at three trial sites (Hwang et al., 2002).

### Conclusion—Fertilizer Application

We summarized 13 articles and found the most consistent improvements in grassland establishment were from applied P, with inconsistent responses for N and K, depending on interactions with species, other nutrients, and competition from unsown species. In general, the literature agrees with the Code 512 General Criteria Applicable to all Purposes, that all plant nutrients and/or soil amendments for establishment purposes should be based on a current soil test. There is sufficient local variation that application rates, methods, and dates should be obtained from local plant materials centers, land grant and research institutions, extension agencies, or agency field trials. In the specific case of grassland establishment, recommendations for fertilizer application based on soil tests should use recommendations for seeding-year stands, because mature-stand recommendations are likely to be different.

### SITE AND SEEDBED PREPARATION, AND SEEDING METHOD

Seeding methods for grassland species range from high-cost, high-input methods such as conventional establishment where the site is fully cultivated into a tilled seedbed, to low-cost, low-input methods such as frost seeding or livestock seeding. Seeding methods have been thoroughly described and reviewed by several authors (Wolf et al., 1996; Cosgrove and Collins, 2003; Masters et al., 2004; Hall and Vough, 2007). This section will focus on

the most common establishment methods related to the Code 512 Purposes.

Once successfully established, forages can be used to improve livestock/wildlife nutrition, reduce soil erosion, improve water quality, and eventually increase C sequestration regardless of the method used to achieve their establishment. In most cases, a variety of planting methods can be used to accomplish the primary intended Code 512 Purpose. A notable exception occurs with species that can only be vegetatively propagated because they do not produce viable seed. In specialized cases such as organic systems that preclude pesticide use, the primary intended purpose for the stand may influence which planting method would be most appropriate. In most cases, differences due to planting methods are usually short-lived and will often disappear by the second year of the stand if not sooner, assuming successful establishment of the desired species is accomplished. Our goal is to evaluate the success and the effects of seedbed preparation and establishment methods on ecosystem services during the establishment period.

The goal of full seedbed preparation using tillage, fertilizer, and lime is to create an environment that optimizes the establishment of seed or vegetative propagules. An ideal seedbed is (1) very firm below planting depth, (2) well pulverized and friable surface soil, (3) not cloddy or puddled, (4) free from competition with resident vegetation, and (5) free of weed seeds (Vallentine, 1989). This latter factor of weed-free soil can rarely be achieved in a cost-effective and practical manner; however, steps should be taken to manage weed competition (see later). This ideal seedbed will enable placement of the seed or vegetative propagules at the proper depth and in firm contact with the soil. This ensures rapid movement of water from the soil to the seed, seedling, or vegetative propagule, resulting in greater likelihood of rapid and uniform germination and early seedling growth that leads to successful stand establishment (Bartholomew, 2005).

Deviations from a tilled and prepared seedbed still need to meet the basic requirement of the seed or vegetative propagules being placed in good contact with the soil at the proper depth



The goal...  
is to create an  
environment that  
optimizes the  
establishment of  
seed”



Use of annual companion crops...is a common and successful practice”

for establishment (Bartholomew, 2005). Poor soil contact can result from cloddy or loose soil and usually results in uneven emergence, slow seed germination, or seedling desiccation, any of which can lead to other problems such as weed competition during the early establishment phase (Hall and Vough, 2007). Thus, alternative establishment methods may require more specific management to accomplish the desired objective of achieving a useable stand, including proper fertility, planting time, weed management, and adequate moisture supply after planting. The desired outcome may be more difficult to accomplish and, therefore, the risk of failure may be higher for alternative methods, yet the effort is environmentally more favorable. So these risks need to be balanced by economic costs and needs for environmental conservation during establishment.

### **Establishment for Forage Production, Livestock and Wildlife Nutrition**

Use of annual companion crops such as spring-seeded small grain species or annual ryegrass when establishing perennial forage species is a common and successful practice, especially across northern latitudes of the USA. Companion crops usually have only short-term negative effects on forage production and nutritive value of the harvested forage (Table 2.3). Harvesting the companion crop as forage instead of grain usually increases weed-free forage yield in the seeding year, especially at the first harvest, and particularly when compared with seedings made without a companion crop or without herbicides.

The nutritive value of the combination of companion crop and perennial forage is usually lower than the nutritive value of the perennial forage crop seeded alone, but with herbicides used for weed control. However, the forage quality of the companion crop can be adequate for many classes of livestock (Sulc et al., 1993b). Although the companion crop does compete with developing perennial forage seedlings and decreases their yield in the seeding year, it reduces the density of weeds which can be even more competitive. If the companion crop has reduced seeding rate or is harvested early for forage to minimize competition to the desirable perennial species, by the second year the perennial forage stand

will produce as well as if it were seeded alone with herbicides (Sulc et al., 1993a).

Use of companion crops for perennial forage establishment is not advisable if it reduces success of the desired perennial species. For example, perennial forage species with poor seedling vigor cannot be easily established with companion crops due to excessive competition (Seguin et al., 1999; Acharya et al., 2006). Recommendations based on local research and proven experience should be followed. The popularity of companion crops has declined with the introduction of effective pre- and postemergence herbicides, however, it remains a viable practice for erosion-prone soils, for organic production, for growers who prefer to not use herbicides, or for situations in which high forage yield is needed in the seeding year.

Using a row-type drill with press wheels to firm seed into a tilled soil is generally considered to be the superior method for planting forages, even with conventional tillage practices. Several studies have demonstrated that drilling with the same seeding rate results in greater forage plant density, faster establishment, and greater seedling growth during the early establishment phase than do broadcast seeding methods, which include broadcast cultipacker seeding (Tesar et al., 1954; Brown, 1959; Hart et al., 1968; Butler et al., 2008). There was no advantage of drilling after the establishment phase (Brown, 1959; Butler et al., 2008) indicating drilling seed is not superior to broadcasting seed on prepared seedbeds beyond the establishment year. Thus, seed placement methods have little effect over the long term provided the seed was placed in good contact with the soil and resulted in an adequate density of established plants.

Past research has shown both positive and negative responses for forage establishment and early-season production when establishing forages with no-till, reduced tillage, or fully tilled seedings (Table 2.5). The studies and discussions in various reviews point out that a range of tillage methods can be used to establish forages successfully (Table 2.5), and achieve forage production for animal nutrition *if* management principles specific to each method are followed (Wolf et al., 1996; Cosgrove and Collins, 2003; Masters et al., 2004; Hall and Vough, 2007).

When using less tillage, especially when introducing new species into existing sods, controlling the existing vegetation and managing residues appropriately are extremely important to achieve acceptable stand establishment (Decker et al., 1969; Seguin, 1998). For example, Cuomo et al. (2001) concluded that suppressing existing vegetation was more important than planting method when legumes are interseeded into cool-season grass pastures. Legumes established more quickly and dominated the sward after a grass sod was killed compared with being chemically suppressed (Koch et al., 1987). With sod seeding, forage yield is usually reduced during the period the existing sod is chemically suppressed and the introduced species becomes established; however, the resultant sward, including the new species, often shows higher yield, forage quality, digestible dry matter, and dry-matter intake by animals (Olsen et al., 1981; Koch et al., 1987).

### Soil Erosion and Water Quality

No research was found comparing establishment methods on soil erosion or water quality. Intuitively, full cultivation carries far greater risk of water or wind erosion, because there is a period of bare soil; however, this risk on flatter soil sites is usually considered acceptable compared to the benefits once the stand is established (Fig. 2.1). No-till establishment, especially on hill slopes, is likely to reduce the risk of erosion markedly compared to a tilled seedbed. The remnant dead vegetation and nondecomposed roots of the suppressed sod offer greater soil protection. In Wisconsin, reduced-tillage methods for establishing alfalfa in spring reduced surface water runoff volume and soil loss under rainfall simulation events (Sturgul et al., 1990). Surface residue reduced soil loss to near zero among tillage treatments, whereas no till after all surface residue had been removed resulted in water runoff and soil losses similar to moldboard plowing.

Companion crops are often touted as a means to reduce soil erosion. In Wisconsin, an oat companion crop with spring-seeded alfalfa reduced soil loss to nearly half of that found when no companion crop was used. But dead crop residue on the soil surface and conservation tillage was even more effective at

reducing soil loss (Wollenhaupt et al., 1995). Therefore, they recommended using crop residue management as a more effective method than companion cropping for erosion control during alfalfa establishment. In Oregon, no-till seeding of perennial ryegrass and tall fescue combined with approx. 9000 kg ha<sup>-1</sup> of straw residue on the soil surface following grass seed harvest reduced estimated soil erosion by 40 to 77% compared with conventional tillage combined with low residue cover (Steiner et al., 2006).

### Biomass

For species with dual-purpose use as forage or biomass, planting methods are equally applicable for either purpose. Although biomass plantings may have harvest schedules different from forage production, this harvesting will not be affected by the establishment method. The optimum establishment methods vary between species, with seeded species such as switchgrass best established in spring by either no-till, reduced-till, or full cultivation, and vegetative species such as miscanthus best established in spring by sprigging of stolons or rhizomes into cultivated seedbeds. In general these biomass species take longer to become established, which lengthens the exposure to potential environmental degradation.

### Carbon Sequestration

The effects of seeding method on C sequestration have not been addressed in the literature. Based on evidence from grain crops, any cultivation during the forage establishment process is almost certain to release large amounts of CO<sub>2</sub> from the soil to the atmosphere (Reicosky and Archer, 2007), or at a minimum, disrupt C sequestration that might have been occurring with the previous vegetation. In addition, there will be release of CO<sub>2</sub> from combustion of fossil fuels during the tillage process. Less disruptive methods such as no till will likely conserve more soil C, but data specific to forage establishment were not found. Skinner and Adler (2010) report positive C sequestration occurred during the 3 yr period it took for switchgrass to establish following a no-till planting in Pennsylvania. In that study, no net C sequestration occurred in Year 4 because the established stand was harvested for biomass.



No-till establishment, especially on hill slopes, is likely to reduce the risk of erosion markedly”

**TABLE 2.5.** Summary of research on planting methods.<sup>1</sup>

Method	Species	Location	Summary	Purpose	Reference
Tillage	Alfalfa, meadow brome grass	Manitoba	Year-1 yield of alfalfa and meadow brome grass were unaffected by NT or CT seeding when canola or field pea were preceding crops; when following wheat the results were variable. With high postseeding rainfall and above-average wheat straw residue, establishment and early growth of meadow brome grass, and to a lesser extent, alfalfa, were often reduced in NT. However, under low postseeding rainfall and average wheat straw residue levels, establishment and seedling development of both alfalfa and meadow brome grass were enhanced in NT vs. CT seeding, probably because of greater soil water conservation. There were no treatment differences for forage yield the year after seeding.	Production	Allen and Entz (1994)
Tillage	Wheat, rye	AR	NT drilled superior to CT drilled and RT broadcast when rains were delayed; otherwise all methods were equal when timely rains promoted seedling emergence and growth in all systems.	Production	Bowman et al. (2008)
Planters	Tall fescue, hardinggrass, tall wheatgrass	TX	With CT, drilling seed resulted in greater forage yield than broadcast seeding.	Production	Butler et al. (2008)
Tillage	Annual ryegrass	LA	Annual ryegrass establishment and early-season production were less consistent with NT than CT; however, NT establishment success improved when managing warm-season grass residue prior to seeding with glyphosate or burning.	Production	Cuomo et al. (1999)
Sod seeding	Alfalfa, red clover, birdsfoot trefoil, kura clover	MN	Suppressing existing vegetation was more important than planting method when renovating cool-season grass pastures with legumes; various methods were successful for establishing legumes with adequate sod suppression.	Production	Cuomo et al. (2001)
Sod seeding	Kleingrass, Illinois bundleflower	TX	Disking or paraquat suppression of a kleingrass sod resulted in significantly higher seedling densities of interseeded Illinois bundleflower than without any sod suppression; broadcasting at twice the seeding rate resulted in equal or higher seedling densities compared with drilling seed.	Production	Dovel et al. (1990)
Companion crop	Alfalfa, oat	SD	Rank of seeding year weed-free forage yield was: Alfalfa plus oat companion for forage > alfalfa + EPTC herbicide > alfalfa alone > alfalfa plus oat companion for grain	Production	Hansen and Krueger (1973)
Planters	Tall fescue, white clover	MD	When planting tall fescue + white clover, drilling seed with a banded fertilizer produced better stands and higher forage yields than broadcast and incorporated fertilizer followed by broadcasting plus cultipacking the seedbed.	Production	Hart et al. (1968)
Companion crop	Oat, alfalfa	IA	Oat companion crop increased forage yield in seeding year and reduced weed density; however, forage quality and alfalfa densities were lower than drilled clear-seeded treatments; no yield or quality treatment differences the year after seeding	Production	Hoy et al. (2002)
Tillage + fertilizer	Alfalfa, orchardgrass, birdsfoot trefoil, timothy	WY	On soils with low pH, surface liming and NT planting resulted in less-vigorous seedlings, slower establishment, and lower seeding year yield than incorporated lime with CT seedbeds	Production	Koch and Estes (1986)

TABLE 2.5. continued.

Method	Species	Location	Summary	Purpose	Reference
Sod seeding	Alfalfa, red clover, timothy	NH	Adding legumes to grass swards can be accomplished without tillage and resulted in increased legume content, improved forage quality, and higher DM intake by dairy heifers. No differences in animal response from sod and conventional seedings. Legumes established more rapidly with sod kill (glyphosate) and dominated the sward compared with sod suppression (paraquat). Where initial fertility was low, tilling was better than sod seeding. Suppressing or killing the sod for legume establishment reduced seeding year yield but increased digestible DM 48% and CP yield 75% the year after seeding compared with unseeded controls plus N fertilizer. Sod seeding with legumes can result in N fertilizer savings and improved nutrient yield where tillage is not practical.	Production	Koch et al. (1987)
Companion crop	Alfalfa, oat	CA	Planting alfalfa with an oat companion increased first-harvest forage yield relative to alfalfa seeded alone. Alfalfa yields at subsequent cuttings the first year were reduced by oat companion crop treatments; however, alfalfa yields the following year were equal in all treatments. The oat companion reduced weed biomass in both the first and second years compared with seeding alfalfa alone.	Production	Lanini et al. (1991)
Tillage - herbicide	Alfalfa, quackgrass	NH	When seeding alfalfa into a quackgrass sod, treating with glyphosate was important for increasing alfalfa and total yields, especially when using MT. Applying glyphosate to control existing sod very near to planting time may, in some cases, lead to reduced alfalfa stand establishment and slower alfalfa seedling growth, possibly due to rapid release of allelopathic compounds from the decaying sod.	Production	Mueller-Warrant and Koch (1980)
Tillage	Ladino clover, red clover, tall fescue	IL	Successful forage stands can be obtained with NT in wheat stubble provided good NT drills are used. Planting forages in late summer in wheat stubble enhanced winter cover, presumably providing better protection from soil erosion and water runoff.	Production and erosion	Olsen et al. (1978)
Sod seeding	Alfalfa, red clover, white clover	IL	Legume establishment in grass sod may be possible without chemical sod suppression, temporary chemical suppression is usually desirable to ensure legume establishment. Legumes enhanced DM yield over the long term; alfalfa was the most productive and long-lived sod-seeded legume; red and ladino clover were well suited for short-term stands.	Production	Olsen et al. (1981)
Companion crop	Kura clover, oat	MN	Oat companion crop increased total weed-free forage yields in Year 1, but reduced kura clover yield by 46% in Year 1 and later years compared with solo seeding with herbicide; seed production only occurred with solo seeding with herbicides; solo seeding with herbicide is more reliable than oat companion crop seeding for kura clover establishment.	Production	Seguin et al. (1999)
Companion crop	Oat, barley, alfalfa	MN	Semidwarf and conventional oat and barley genotypes performed similarly as companion crops for alfalfa establishment; companion crops reduced weed biomass and increased alfalfa plant mortality during establishment but did not lower alfalfa yield at later harvests.	Production	Simmons et al. (1995)

TABLE 2.5. continued.

Method	Species	Location	Summary	Purpose	Reference
Tillage	Perennial ryegrass, tall fescue, creeping red fescue	OR	NT seeding combined with high straw residue cover reduced estimated soil erosion 40–77% compared with CT and low-residue cover seeding of cool-season grasses. NT plus high-residue cover reduced costs 60–84%.	Soil erosion	Steiner et al. (2006)
Tillage	Perennial ryegrass, tall fescue, creeping red fescue	OR	Seed yields of cool-season grasses that were NT were equal to or higher than when established with CT. High straw residue cover at seeding did not adversely affect grass seed yield	Production	Steiner et al. (2006)
Tillage	Alfalfa	WI	Year-1 alfalfa yield and quality did not vary among moldboard plow, chisel plow, and NT seedbed preparation treatments.	Production	Sturgul et al. (1990)
Tillage + companion crop	Alfalfa, oat	WI	Relative to moldboard plowing for seedbed preparation, chisel plowing reduced surface water runoff volume 23–72% and NT seeding reduced volumes 59–100%; soil loss was reduced 24–64% with chisel plow and 71–100% with NT; however, NT with all surface residue removed had the highest runoff volumes for four of five rainfall simulations, and soil losses were similar to moldboard plowing for all rainfall simulations; there was no evidence of canopy development effect on runoff volumes; however, canopy development contributed to reduced soil losses within treatments, with the greatest reduction in the moldboard plus nurse-crop treatment that, at near full canopy, reduced soil loss by 96% compared with 0% canopy cover in the same treatment.	Soil erosion	Sturgul et al. (1990)
Companion crop	Annual ryegrass, alfalfa	WI	Annual ryegrass companion crops for alfalfa establishment increased forage yield but decreased forage quality in Year 1 compared with solo-seeded alfalfa. Where conditions favored vigorous ryegrass growth, alfalfa stand establishment was reduced. Early-maturing diploid annual ryegrass cultivars were the least competitive with alfalfa establishment.	Production	Sulc and Albrecht (1996)
Companion crop	Annual ryegrass, alfalfa	WI	Rainfall quantity and distribution during the season, companion crop species and cultivar selection, seeding rate, and harvest management affect forage yield and alfalfa plant density in the year after establishment. Ryegrass was less competitive with alfalfa than oat in dry years, but the reverse was true in wet years. Early removal of the companion crop as forage reduced the competition with alfalfa.	Production	Sulc et al. (1993a)
Companion crop	Annual ryegrass, alfalfa	WI	Ryegrass–alfalfa mixtures can provide higher-quality forage than oat–alfalfa mixtures in the first harvest of Year 1, but not at subsequent harvests, especially when adequate rainfall promotes vigorous seeding year ryegrass growth.	Production	Sulc et al. (1993b)
Planters	Alfalfa, birdsfoot trefoil	MI	Banding seed on the soil surface directly over a P-fertilizer band 4 cm deep resulted in more legume seedlings and taller, more vigorous plants than were obtained with broadcast seed on similarly fertilized soil. Seedlings had to be directly over or within 2.5 cm of the fertilizer band to obtain over 60% of their P from the fertilizer during the first 2 mo of growth.	Production	Tesar et al. (1954)

TABLE 2.5. continued.

Method	Species	Location	Summary	Purpose	Reference
Frost seeding	Smooth brome grass, orchardgrass, perennial ryegrass, reed canarygrass, timothy, red clover	WI	Frost seeding temperate forage species into aging alfalfa can increase plant diversity and forage yield while suppressing weeds; species differed in rate of establishment.	Production	Undersander et al. (2001); Casler et al. (1999)
Tillage · companion crop	Alfalfa oat	WI	Seeding alfalfa with an oat companion reduced soil loss to nearly 50% that of alfalfa sown alone, but crop residue on the soil surface with CT was more effective than a companion crop in reducing soil loss; authors concluded crop-residue management is more effective than companion cropping for erosion control during alfalfa establishment. Surface water runoff volumes were not consistently reduced by CT and were dependent on previous site conditions.	Soil erosion	Wollenhaupt et al. (1995)
Companion crop	Annual ryegrass, festulolium	WI	Annual ryegrass or festulolium can be used as companion crops for perennial forage legume establishment to enhance overall quality of harvested forage in the seeding year compared with an oat companion and will increase yield over solo seeded alfalfa; however, in years that favor aggressive ryegrass growth, legumes establish more slowly and may produce less forage even in Year 2.	Production	Wiersma et al. (1999)

<sup>1</sup>Abbreviations: CT, conventional tillage (usually by full cultivation); NT, No-tillage (or conservation tillage); MT, minimum tillage; RT, reduced; DM, dry matter; CP, crude protein

### Specialized Methods

The review of Wolf et al. (1996) described 27 forage establishment methods. Although some were variations of the two main methods, full cultivation or no-till establishment, there are many other specialized establishment methods that have used successfully. The most common methods are described.

Sprig seeding is used for establishing plants vegetatively, usually from plant stolons, after tillage. This is most commonly used for bermudagrass (Greene et al., 1992). Stolons are harvested from an established nursery field and transported to a prepared target area. The stolons are distributed over the land surface by hand or by machine, and then buried to a shallow depth with the use of a lightweight disk at a low angle of cultivation.

Frost seeding is used to introduce species, especially legumes, into existing sods by broadcasting the seed on frozen soils and relying on the freeze–thaw cycles in late winter to achieve the necessary seed–soil contact

for germination and emergence in the spring (Undersander et al., 2001; Blaser et al., 2006, 2007). This method has been used successfully by many forage producers, and has been shown to increase plant diversity and forage yield while suppressing weeds (Casler et al., 1999; Undersander et al., 2001). The freeze–thaw cycles that occur in later winter and early spring provide sufficient surface disturbance that seed have adequate soil contact for establishment.

Frost seeding can be suitable for fast-establishing species such as most legumes, but is not suitable for most grass species. The proportion of seed that actually emerges can be as low as 5–10% of seed sown, so higher seeding rates are recommended. The likelihood of successful establishment from broadcast seeding into established vegetation can be improved by minimizing the surface vegetation to allow seed–soil contact, by using livestock to tread seed into the soil, and by controlling growth of the existing vegetation with herbicides or grazing to reduce competition

with the establishing seedlings for light (Blackmore, 1965; Lambert et al. 1985).

Natural reseeding is the application of knowledge about the reproductive processes within natural grasslands or managed grasslands. Naturalized annual species such as annual poa, subterranean clover and annual lespedeza are dependent on natural reseeding for their ongoing survival. In the case of short-lived perennial species, natural reseeding can be encouraged by delaying grazing or harvest until seed ripens and drops onto the soil; however, this is only relevant for long-lived seed such as those legumes that are not autotoxic, and is not recommended for grass species that tend to have short seed longevity in soil. Secondly, the canopy needs to be managed during seed germination to reduce competition as the young seedlings become established. Although it can seem attractive to generate a seed population by natural reseeding, the seed is typically of low quality, and establishes poorly in the competitive stand, so other pasture improvement mechanisms are usually preferred.

Natural reseeding was used successfully in a wheat–fallow rotation in the northern Great

Plains (Carr et al., 2005) by introducing forage legumes into the rotation by no-till planting. The perennial rotation improved soil structure, improved nutrient cycling, reduced soil erosion, and improved economic and environmental sustainability of crop production. The main requirement was the production of sufficient legume seed each year to regenerate the stand the following year. Species with sufficient natural regeneration were balansa, berseem, crimson, persian, and red clovers; birdsfoot trefoil; and black and burr medics (Carr et al., 2005).

Spray seeding is a method where the seed is broadcast onto the soil surface with the use of a variety of liquid or dry carrier materials, which may include additives such as nutrients and fungicides. The resultant mixture is sprayed or broadcast over the target area. This method is most commonly used for small areas that may be too steep for mechanical cultivation, and is not widely used for field seedings; however, spray seeding followed by rolling with a cultipacker has been used successfully on flatter sites and conventionally tilled seedbeds, which allows planting of large areas in a short time.



White clover 4 mo after frost seeding in March into a tall fescue sod in Ohio. The pasture was grazed to expose bare soil for seeding, then control grazed to reduce competition. Credit: David Barker, Ohio State University.

### Conclusion—Site Preparation and Planting Methods

General Criteria of Code 512 specify following recommendations for planting methods obtained from the plant materials program, land grant and research institutions, extension agencies, or agency field trials. In our summary of 28 publications we found satisfactory establishment from many methods, typically with a trade-off between cost and establishment success. Given the number of site-preparation options, the number of establishment options, the number of species and their intended purpose, the best advice on seeding method and management will come from local specialists. They know the characteristics of the local climate, soils, and adaptation of the plant species proposed to extrapolate the principles from other locations and link with the overall goals of the producer to maximize the probability of success.

The Code 512 Criteria also specify preparation of the site to provide a medium that does not restrict plant emergence. Although supported in broad terms by the literature, caution is required, because:

1. Excessive site preparation and cultivation can disrupt the structure of some soils to an extent that might impair emergence, e.g., if the soil becomes crusted following rainfall.
2. Excessive site preparation may detract from other purposes, such as erosion control, C sequestration, or cost effectiveness.
3. Cultivation can stimulate weed germination.
4. Some methods (frost seeding and no-till) do not require the same extent of site preparation as full cultivation.

The Code 512 Considerations specify that where air-quality concerns exist site preparation and planting techniques that will minimize airborne particulate matter generation and transport should be considered. The general literature supports the use of alternatives from full tillage to reduce dust and disturbance that frequently are associated with relatively bare soils. These data should be transferable to forage plantings. The Code 512 Plans and Specifications also specify site preparation,

seedbed preparation, and method of planting. Given the environmental and economic costs of these steps, thorough assessment at the local level of the various options for site preparations and establishment is imperative.

### CLIMATIC FACTORS AFFECTING SEEDING DATE

Seeding date is one of the most critical components of establishment success. The USA has such a wide range of environments that successful establishment may occur somewhere in almost every month of the year. The two climatic variables having the greatest influence on establishment success are temperature (Townsend and McGinnies, 1972a; Hsu et al., 1985a, 1985b; Brar et al., 1991; Kalburtji et al., 2007) and soil moisture (Roundy, 1985; Clem et al., 1993; Awan et al., 1995).

Each region has very specific periods within which planting is recommended, based largely on a high probability of adequate soil temperature and moisture (Sulc and Rhodes, 1997; Table 2.6). Typically, cool-season grasses are established in late summer in northern states or in autumn in the transition zone and lower latitudes (see Figs. 1.1 and 1.2). Legumes can also be planted at the same time, but require more time than cool-season grasses to achieve sufficient winter hardiness. Most warm-season species have higher minimum temperatures for germination and seedling growth and are planted in late spring. There was no evidence in the literature that planting date should change with the intended purpose of the resultant stand.

**Soil Moisture.** Rainfall subsequent to planting may have more influence on establishment success than moisture conditions at the time of planting (Bell et al., 2005). Barker et al. (1988) analyzed 14 establishment studies and found time to emergence was most closely correlated with rainfall occurring the week immediately after seeding. Cumulative rainfall during the 2 wk after seeding was poorly correlated with time to emergence, and cumulative rainfall during the month after seeding was unrelated to emergence. Germination percentages of crested wheatgrass, intermediate wheatgrass, smooth brome grass, and Russian wildrye



...thorough assessment at the local level of the various options for site preparations and establishment is imperative.”

**TABLE 2.6.** Summary of research on latest date for fall planting at various locations and forage species.

Species	Location	Date	Reference
Alfalfa	Southern Saskatchewan	1 November	Kilcher (1961)
Alfalfa	Northern Wisconsin	1 August	Undersander et al. (1991)
Alfalfa	Southern Wisconsin	Mid-August	Undersander et al. (1991)
Alfalfa	Northern Michigan	1 August	Tesar (1983)
Alfalfa	Southern Michigan	Mid-August	Tesar (1983)
Alfalfa	North Dakota	1 August	Undersander et al. (1991)
Alfalfa	Minnesota	1 August	Undersander et al. (1991)
Alfalfa	Northern New York	Early August	Cherney and Hansen (2011)
Alfalfa	Southern New York	Mid-August	Cherney and Hansen (2011)
Alfalfa	Pennsylvania	1 August	Hall (1995)
Alfalfa	Central Pennsylvania	Mid-August	Terrill (1961)
Alfalfa	Southern Pennsylvania	1 September	Terrill (1961)
Alfalfa	Maryland	10 September	Hofmann and Decker (1971)
Alfalfa	North Carolina	Mid-September	Mueller and Chamblee (1984)
Alfalfa	Central California	Mid-September	Marble and Peterson (1981)
Birdsfoot trefoil	New York	Late July	Cherney and Hansen (2011)
Birdsfoot trefoil	Pennsylvania	1 August	Hall (1995)
Creeping foxtail	Wisconsin	Mid-August	Undersander and Greub (2007)
Crested wheatgrass	Southern Saskatchewan	1 November	Kilcher (1961)
Crested wheatgrass	Montana	28 September	White and Currie (1980)
Green needlegrass	Southern Saskatchewan	1 November	Kilcher (1961)
Intermediate wheatgrass	Southern Saskatchewan	1 November	Kilcher (1961)
Intermediate wheatgrass	Montana	28 September	White and Currie (1980)
Orchardgrass	Wisconsin	Mid-August	Undersander and Greub (2007)
Orchardgrass	Pennsylvania	Mid-August	Hall (1995)
Perennial ryegrass	Wisconsin	Mid-August	Undersander and Greub (2007)
Perennial grasses	Northern New York	Mid-August	Cherney and Hansen (2011)
Perennial grasses	Southern New York	Late August	Cherney and Hansen (2011)
Perennial ryegrass	Pennsylvania	Late August	Hall (1995)
Red clover	Pennsylvania	1 August	Hall (1995)
Reed canarygrass	New York	Late July	Cherney and Hansen (2011)
Reed canarygrass	Pennsylvania	1 August	Hall (1995)
Reed canarygrass	Wisconsin	Mid-August	Undersander and Greub (2007)
Russian wildrye	Southern Saskatchewan	1 November	Kilcher (1961)
Russian wildrye	Montana	12 September	White and Currie (1980)
Smooth brome grass	Wisconsin	Early August	Undersander and Greub (2007)
Tall fescue	Wisconsin	Mid-August	Undersander and Greub (2007)
Timothy	Wisconsin	Early September	Undersander and Greub (2007)
Thickspike wheatgrass	Southern Saskatchewan	15 September	Kilcher (1961)

were decreased and time to germination was delayed by 1–2 wk as soil moisture decreased from field capacity to permanent wilting point (McGinnies, 1960).

Planting during periods of high soil moisture may result in soil compaction by heavy equipment or damage to soil structure from cultivation when the soil is too wet. The

sensitivity of germination and early growth to low soil moisture varies with location and establishment method. Broadcast planting methods (such as frost seeding) are more sensitive to variable temperature and precipitation than methods that insert seed into the soil.

Soil moisture for germination and establishment can be more easily controlled in irrigated systems. In semi-arid regions where summer precipitation is inconsistent, the soil should be irrigated prior to fall seeding, leaving sufficient time for a final cultivation before planting to reduce weeds and for sufficient seedling growth before frost. Where flood irrigation is used, fields must be leveled to prevent high or low spots where seedling establishment could fail because of drought or flooding stress. Where sprinkler irrigation is available, the surface soil can be kept moist during germination and establishment by short, frequent irrigations. For a high-value cash crop such as alfalfa hay that will be flood-irrigated for regrowth, use of a sprinkler irrigation system for establishment may be justified. Other considerations for establishment of alfalfa under irrigation can be found in Summers and Putnam (2008).

Seed germination rate is the first critical step to successful establishment. Germination usually occurs near the soil surface, and studies show that measured moisture of the upper 10 or 15 cm of the soil are poor predictors of establishment success. In contrast, Awan et al. (1995) measured moisture of just the surface soil using a novel method and found those measurements could be used to predict germination success.

Temperature. Among 10 perennial legumes, alfalfa germinated readily at day/night temperatures that ranged from 8/2°C to 24/18°C (Hill and Luck, 1991). In contrast, birdsfoot trefoil and red, white, kura, and strawberry clovers germinated readily at the three higher temperatures and had depressed germination at 12/6 or 8/2°C. Crownvetch, cicer milkvetch, and sericea lespedeza germinated and developed above 20°C. Rate of seedling growth for a species had a response to temperature that was similar to the response of germination (Hill and

Luck, 1991). The optimum germination and emergence temperature for six vetch species was between 18°C and 23°C, whereas the optimum temperature for root growth of these species was slightly higher, between 20°C and 25°C (Mosjidis and Zhang, 1995). Root growth is critical to ensure water and nutrient uptake.

Planting of cool-season forages in spring in many locations is more sensitive to excessive soil moisture than to cool temperatures. However, the establishment of warm-season grasses is slowed by low soil temperatures. Although stratification improved germination of the warm-season perennial grasses big bluestem, caucasian bluestem, indiangrass, and switchgrass (Hsu et al., 1985a, 1985b), rates of warm-season grass development in the field were more rapid for later planting dates (Hsu and Nelson, 1986b). The optimal planting dates in Missouri for these grasses fell between late April and mid-May, when soil temperature was warmer than 10°C, but before soil moisture was depleted (Hsu and Nelson, 1986a).

Eastern gamagrass has a high level of seed dormancy that can be improved by natural stratification. Seed planted in Iowa in either mid-August or late October experienced natural winter stratification and had higher germination in spring than seed planted in spring or summer (Gibson et al., 2005). But this was not found in all cases (Aberle et al., 2003). Dallisgrass germination was improved by flooding and high defoliation intensity of the competing plants which reduced evapotranspiration and created gaps in the canopy that increased the red:far-red light ratio that stimulates growth and significantly improved establishment (Cornaglia et al., 2009). Mosjidis (1990) found that the germination percentage of eight genotypes of sericea lespedeza, a warm-season legume, increased linearly by 20% for every 3°C as day/night temperatures increased from 18/14°C to 30/26°C; the optimum temperature for germination was between 20°C and 30°C (Qiu et al., 1995).

Planting cool-season grasses and legumes in late summer or early autumn is advantageous because it allows an annual crop to be harvested before planting, and because warmer, drier conditions mean that weed and disease



Seed germination rate is the first critical step to successful establishment.”

pressures are generally lower than in early spring. It is recommended that cool-season species be planted early enough for 6 wk of shoot and root development and adequate carbohydrate storage to occur before the first killing frost (Cosgrove and Collins, 2003). In Minnesota, seedlings of the legumes alfalfa, red clover, sweetclover, and alsike clover could not develop adequate winter hardiness until they had developed about seven to nine trifoliate leaves (Arakeri and Schmid, 1949).

Hall (1995) and Undersander and Greub (2007) reviewed the literature on recommended late summer/early autumn planting dates for alfalfa. In Pennsylvania, Hall (1995) seeded alfalfa, birdsfoot trefoil, red clover, orchardgrass, perennial ryegrass, and reed canarygrass in spring and found seeding-year yield decreased linearly with each day of delay after the recommended seeding date. In Wisconsin, Undersander and Greub (2007) evaluated late-autumn seeding dates for orchardgrass, smooth brome grass, timothy, reed canarygrass, perennial ryegrass, and tall fescue. Based on germination in autumn and establishment in early spring the dormant seeding failed four times out of five, and is not recommended. However, in the dry upper Great Plains, with 370 mm average annual rainfall, 1 November seedings were consistently more successful than May seedings for

alfalfa, crested wheatgrass, green needlegrass, intermediate wheatgrass, and Russian wildrye (Kilcher, 1961).

Fall plantings of alfalfa, crested wheatgrass, smooth brome grass, and slender wheatgrass survived winter in the northern Great Plains if they reached the three-leaf stage before the ground froze (White and Horner, 1943). Planting by 1 September was recommended if there was moisture in the soil, because germination was slowed at later dates as soil temperatures decreased. Under dryland conditions in Montana, mid- to late-September plantings resulted in good establishment of crested wheatgrass, intermediate wheatgrass and Russian wildrye (White and Currie, 1980). These species survived planting as late as mid-October if they produced two leaves before the soil froze (White, 1984). These small seedlings grew significantly more the following year than did dormant-seeded plants that germinated in spring. Seedlings with three or more leaves at the beginning of spring could be grazed by midsummer of the following year, and produced more herbage dry matter by autumn than seedlings with fewer leaves in spring.

Ries and Svejcar (1991) tied the successful establishment of crested wheatgrass and blue grama to their development of adventitious (i.e., nodal) roots into subsoil water. The cross-sectional area of xylem in adventitious roots was several times that of seminal roots, indicating adventitious roots were needed to transport sufficient water to support continuing leaf expansion. By the time adventitious roots were 8–10 cm long, four–six leaves had developed on the main axis and tillering had begun.

The usefulness of tillering as a measure of grass seedling establishment was confirmed in a study of prairiegrass, grazing brome grass, and orchardgrass that showed seedlings did not survive winter unless they had begun to tiller before ceasing growth in autumn (Sanderson et al., 2002). Undersander and Greub (2007) also identified tillering following fall planting was the factor best correlated with yield in the following spring.

Some nonleguminous forbs, often annuals, have high forage quality and have potential for use in grassland systems. Turnip planted

A cultipacker-type seed drill used for a spring seeding in Ohio. Seed is dropped between the front and back rollers, which are offset slightly so the back roller covers the seed. Credit: Mark Sulc, The Ohio State University.



in late July in West Virginia produced the greatest top and root dry matter that autumn compared to earlier or later plantings (Jung and Shaffer, 1995). In contrast, mid-September seedlings of chicory and plantain developed two fully expanded leaves, but were not developed sufficiently to overwinter in Pennsylvania (Sanderson and Elwinger, 2000).

The average worldwide air temperature has increased by about 1°C over the last century (Easterling et al., 1997) and grassland establishment has likely been affected. A long-term study in northeast Colorado determined that annual net primary production of buffalograss, the dominant native grass of the shortgrass prairie, decreased with increase in minimum air temperature, whereas that of both native and exotic forb species increased (Alward et al., 1999). In Florida, studies of the direct effect of increased temperature and CO<sub>2</sub> concentration demonstrated that rate of photosynthesis and resulting rates of establishment and initial plant growth increased with higher CO<sub>2</sub> concentrations (Fritschi et al., 1999). Rhizoma peanut benefited more from higher CO<sub>2</sub> concentrations than did bahiagrass, but temperature increase benefited biomass production of bahiagrass more than rhizoma peanut (Fritschi et al., 1999). For the future these responses to global change need to be researched, including any environmental impact that might occur during establishment.

### Conclusion—Planting Date

The Code 512 General Criteria specify recommendations for planting dates obtained from the plant materials program, land grant and research institutions, extension agencies, or agency field trials. These principles are well established for most geographic areas and focus on temperature and water as primary factors. However, rather than basing seeding time or method on the current temperature and moisture conditions, the literature indicates planting should be timed to precede a sufficient period of favorable temperature and rainfall.

No studies were found describing fall seeding and dormant seeding effects on soil erosion or ecosystem services. But based on other data with cover crops it is presumed that with little ground cover and small plants there would be environmental risks associated with

these seeding methods. Timing seeding to ensure tillers can develop should help reduce the areas bare of ground cover, and having a better-developed adventitious root system should improve the capacity of the seedlings to stabilize the upper layers of soil. These topics need more research on the environmental risks of having minimal ground cover over winter. This also applies to plantings of annual forbs and expectations of additional risks due to climate change.

### RATES OF SEEDING

Seeding rate is one of the most important variables determining the success of a new seeding. Seeding rate can be measured as either the weight of seed per unit area, or the number of seeds per unit area. The conversion between these two measures is the specific seed weight (i.e., g seed<sup>-1</sup>), and this conversion varies among species, cultivars, and even seed lots. Seeding rates should be based on the delivery of PLS per unit area, and thus also needs to account for hard seed, the percent germination of the seed being planted, and the presence of inert materials such as impurities and seed coatings. To evaluate the criteria and purposes of the standard we summarized 25 articles that evaluated the effect of seeding rate on grassland establishment, forage and biomass production, and forage nutritive value (Table 2.7). No study was found that related seeding rate uniquely to ecosystem purposes such as soil erosion, water quality, C sequestration, or wildlife.

Recommended seeding rates vary by species, location and intended use of the stand. The recommended rates are usually not a specific value, but a defined range of number of seed to apply per unit area. Recommended seeding rates have been determined over the years from research and experience in the field (Table 2.7). Recommended rates tend to be higher for broadcast than drilled stands to offset poorer seed–soil contact and are lower in drier climates. Drier climates typically have less seed and seedling mortality due to diseases, and higher seeding rates can decrease stand productivity because of excessive intraspecific competition for water. Lower rates are also usually recommended for conservation plantings where ground cover and not forage production may be the primary objective.



Seeding rates should be based on the delivery of PLS per unit area”

**TABLE 2.7.** Summary of research on seeding rates of forages.<sup>1</sup>

Species	Seed rates tested	Optimum or recommended seeding rate	Other notes	Location	Reference
<b>Annual and companion crops</b>					
Triticale	50, 75, 100 kg ha <sup>-1</sup>	100 kg ha <sup>-1</sup>	Optimal rate was 75 kg ha <sup>-1</sup> for grain	Alabama	Bishnoi (1980)
Wheat, winter rye	50, 75, 100 kg ha <sup>-1</sup>	75–100 kg ha <sup>-1</sup>	Optimal rate was 50 kg ha <sup>-1</sup> for grain	Alabama	Bishnoi (1980)
Wheat, triticale	100–400 seed m <sup>-2</sup>	300–400 seed m <sup>-2</sup>	Oversown with red clover by frost seeding; seeding rates impacted red clover dry matter within specific harvest periods, but the impact diminished with time and had no effect on seasonal forage total or subsequent spring yield of red clover	Iowa	Blaser et al. (2007)
Triticale, companion to alfalfa	198–594 seed m <sup>-2</sup>	374 PLS m <sup>-2</sup>	Quadratic grain yield response, maximum profit at 374 seeds m <sup>-2</sup> . Increasing triticale seeding rate had no effect on alfalfa density and yield.	Iowa	Gibson et al. (2008)
Turnip	1.7–5.0 kg ha <sup>-1</sup>	Not stated	Seeding-rate effects were significant for yield of tops and roots only 10% and 5% of the time, respectively. This was not expected, but may have been because of seeding in rows.	Pennsylvania	Jung and Shaffer (1993)
Sudangrass, sorghum · sudangrass	13.5–54 kg ha <sup>-1</sup>	Not stated	Plant density and total seasonal forage yield increased as seeding rate increased to the highest rate, especially at the narrow row spacing. Increasing seeding rate reduced crude protein and increased lignin content for the first harvest of the three-cut system, but there was no seeding-rate effect on forage quality of subsequent cuttings.	Wisconsin	Koller and Scholl (1968)
Oat, companion crop to alfalfa	0–36 kg ha <sup>-1</sup>	18 kg ha <sup>-1</sup>	Oat companion crop at 9 kg ha <sup>-1</sup> dramatically increased forage yield compared with no oat companion, and yield increases at higher oat seeding rates were small. Highest forage yields were predicted to occur at oat seeding rates of 24–27 kg ha <sup>-1</sup> ; however, oat at 18 kg ha <sup>-1</sup> was considered best for optimizing yields, reducing weeds, and not affecting alfalfa yield the year after seeding (oat always reduced alfalfa yield in Year 1).	California	Lanini et al. (1991)
Barley, oat, triticale with undersown berseem clover	30–240 plants m <sup>-2</sup>	60–90 plants m <sup>-2</sup>	Cut-1 total yield increased and clover content decreased with increasing cereal density. Berseem clover regrowth (cut 2) was lowest for intercrops with the highest cereal density and increased linearly as cereal density decreased. Effect of cereal density on total seasonal yield was inconsistent across years, but seeding cereals to achieve plant density of 60–90 plants m <sup>-2</sup> (25–40% of full recommended rate) usually improved forage quality without reducing total season yield of cereal–berseem clover intercrops.	Alberta	Ross et al. (2004)

TABLE 2.7. continued.

Species	Seed rates tested	Optimum or recommended seeding rate	Other notes	Location	Reference
Perennial and biennial species					
Alfalfa	4.5–17.9 kg ha <sup>-1</sup>	13.5 kg ha <sup>-1</sup>	Under irrigation, each increase in seed rate increased forage yield in Year 1. Under dryland, no yield differences above 13.5 kg ha <sup>-1</sup> seed rate in Year 1. Year 2 yield increased up to 9 kg ha <sup>-1</sup> at one location and up to 13.5 kg ha <sup>-1</sup> at the two other locations. Crude protein content of forage was not affected by seed rate. Root and crown weight of alfalfa decreased as seed rates increased up to 13.5 kg ha <sup>-1</sup> . At 4.5 kg ha <sup>-1</sup> , alfalfa plant size the year after seeding did not sufficiently compensate to maintain yield.	South Dakota	Hansen and Krueger (1973)
Alfalfa	3–27 kg PLS ha <sup>-1</sup>	17 kg ha <sup>-1</sup>	Initial seedling densities were a near linear function of seeding rate, and those rankings remained consistent as stands thinned over 4 yr; plant mortality was much greater at high than low densities in Year 1; doubtful that rates above 17 kg ha <sup>-1</sup> would increase useful life of the stand and provided no long-term measurable benefit; rates below 17 kg ha <sup>-1</sup> had lower plant density for up to 4 yr after planting.	Missouri, Pennsylvania	Hall et al. (2004)
Alfalfa	1.1–22.4 kg ha <sup>-1</sup>	7.8 kg ha <sup>-1</sup>	Recommended rate of 7.8 kg ha <sup>-1</sup> in Montana to obtain 30 seedlings m <sup>-1</sup> of row; seeding-year yield was directly proportional to seeding rate, but yield the following year was not affected by seeding rate.	Montana	Cooper et al. (1979)
Alfalfa	10–40 kg ha <sup>-1</sup>	10 kg ha <sup>-1</sup>	At the lowest seeding rate, 40–52% of seeds produced established plants, decreasing to 31–44% at the highest seeding rate. Stand density declined most rapidly in the first year. By Year 4, greatest percentage plant mortality had occurred at the highest seeding rate (75–85%) compared with 49–68% mortality of original emerged plants at the low seeding rate. Seed rate affected total 3-yr yield in one of three experiments, and had little or no influence of crude protein and leaf-to-stem ratio.	Spain	Lloveras et al. (2008)
Alfalfa, under oat companion	18–36 kg ha <sup>-1</sup>	No effect	Alfalfa seeding rate did not impact yield or forage composition.	California	Lanini et al. (1991)
Alfalfa and red clover, seeded into suppressed grass sod	4.4–17.6 kg ha <sup>-1</sup>	17.6 kg ha <sup>-1</sup>	Seeding rate effects on legume yield were dependent on location, legume species and grass competitiveness. Seeding rates of at least 17.6 kg ha <sup>-1</sup> appeared to increase establishment year alfalfa and red clover yields when high levels of grass competition exist, and alfalfa may benefit more from higher seeding rates than red clover.	Minnesota	Sheaffer and Swanson (1982)

TABLE 2.7. continued.

Species	Seed rates tested	Optimum or recommended seeding rate	Other notes	Location	Reference
Red clover	0–1500 seed m <sup>-2</sup>	900–1200 seeds m <sup>-2</sup>	Frost seeded into winter cereals, 11–40% of red clover seed established mature plants with actual densities of 46–314 plants m <sup>-2</sup> ; increasing seeding rate increased DM yield but had no effect on forage quality.	Iowa	Blaser et al. (2006, 2007)
Red clover, with and without timothy or tall fescue	6–18 kg ha <sup>-1</sup>	12 kg ha <sup>-1</sup>	Total mixture forage yield, digestible organic matter, and crude protein content were not markedly affected by red clover seed rate; but red clover DM, DOM, and CP were increased as red clover seed rate was raised due to increases in red clover component.	Scotland	Frame et al. (1985)
Tall fescue, with red clover	6–18 kg ha <sup>-1</sup>	Not stated	Tall fescue increased DM yield by 10 and 29% in Years 1 and 2, respectively, compared with red clover alone, but did not increase total forage organic matter digestibility, but decreased crude protein content. Increasing grass seed rate intensified the effects as it decreased the red clover component in the sward.	Scotland	Frame et al. (1985)
Timothy, with red clover	2–6 kg ha <sup>-1</sup>	2–4 kg ha <sup>-1</sup>	Timothy increased DM yield by 6.5 and 10% in Years 1 and 2, respectively, compared with red clover alone; timothy increased total forage organic matter digestibility, but decreased CP content. Increasing grass seed rate intensified the effects as it decreased the red clover component in the sward.	Scotland	Frame et al. (1985)
Perennial ryegrass	10–30 kg ha <sup>-1</sup>	Not stated, no differences	All treatments sown with white clover at 3 kg ha <sup>-1</sup> ; grass seed rate did not affect total DM production or white clover performance.	Scotland	Frame and Boyd (1986)
Bahiagrass	5.6–50.4 kg ha <sup>-1</sup>	Not stated, no long term advantage—higher rates	Increasing seeding rate increased bahiagrass emergence, tiller density (nearly linearly), and Year-2 cover, but yield advantages were small; advantages of higher rates were short lived.	Georgia, Florida	Gates and Mullahey (1997)
White clover, perennial ryegrass	10/0, 8/5, 5/10, 3/15, 0/20 kg ha <sup>-1</sup> for white clover/ryegrass	Not stated	Sowing rate had large effect on clover content in Year 1, and higher clover sowing rate gave higher production in the first year, but this effect disappeared by Year 3; there was little effect of sowing rate on crude protein content; amount of DM removed by grazing decreased as ryegrass sowing rate increased (clover content decreased) in the first year, but this effect disappeared by Year 3.	Australia	Kelly et al. (2005)

TABLE 2.7. continued.

Species	Seed rates tested	Optimum or recommended seeding rate	Other notes	Location	Reference
Big bluestem	110–440 PLS m <sup>-2</sup>	110–220 PLS m <sup>-2</sup> , with herbicides	Big bluestem frequency usually increased with increasing seeding rate; successful establishment occurred in three of four environments at 110 PLS m <sup>-2</sup> , and in all environments at the higher seeding rates; seeding rate influenced yield in three of four environments; if pre-emergent herbicides are used, high-yielding stands of big bluestem can be established at seeding rates of 110 or 220 PLS m <sup>-2</sup> .	Nebraska	Masters (1997)
Hairy vetch, with wheat	0–162 PLS m <sup>-2</sup> for HV, 324 PLS m <sup>-2</sup> for wheat	For high-quality seed vetch at 162 PLS m <sup>-2</sup>	Forage yield decreased but crude protein content and digestibility increased with increasing vetch seeding rate, which was a function of the increasing vetch component in mixture.	Illinois	Roberts et al. (1989)
Switchgrass	Evaluated varying grid frequency levels on farmer fields	40% grid frequency	Establishment-year stand grid frequencies of 40% or greater can be considered an establishment-year stand threshold indicating successful establishment and subsequent postplanting year biomass yields for switchgrass. Establishment-year grid frequency of 25% would be adequate for conservation plantings where no harvests were planned for several years.	Nebraska, South Dakota, North Dakota	Schmer et al. (2005)
Ryegrasses, companion to alfalfa	215–645 PLS m <sup>-2</sup>	215 PLS m <sup>-2</sup>	Increasing ryegrass seeding rate had no effect on total mixture Year-1 yield in environments with adequate rain but decreased forage yield in dry years. Seeding-year alfalfa yield was decreased by increasing ryegrass seeding rate. The lowest ryegrass seeding rate reduced competition with alfalfa, improved forage quality in the seeding year, and reduced the changes of suppressing alfalfa stand establishment.	Wisconsin	Sulc et al. (1993a)
Smooth brome grass, orchardgrass, perennial ryegrass, reed canarygrass, red clover	0–880 PLS m <sup>-2</sup>	Orchardgrass > 220 PLS m <sup>-2</sup> ; timothy > 440 PLS m <sup>-2</sup> ; smooth brome grass, 100–200 PLS m <sup>-2</sup> most economical	Species were frost seeded into aging alfalfa stand. Forage yield increased with seeding rate at sites with the greatest initial establishment of frost-seeded species, but the response was highly variable. Generally, the fast-establishing species (i.e., perennial ryegrass, orchardgrass, and red clover) had significant responses of grass or legume dry matter contribution to increasing seeding rate, whereas the slow species (i.e., reed canarygrass, smooth brome grass, and timothy) did not.	Wisconsin	Undersander et al. (2001)

TABLE 2.7. continued.

Species	Seed rates tested	Optimum or recommended seeding rate	Other notes	Location	Reference
Switchgrass	3.4–16.8 PLS m <sup>-2</sup>	3.4 kg PLS ha <sup>-1</sup>	Greater seeding rates increased seedling number, tiller number, and forage yield, but slightly decreased digestibility and crude protein of the forage. Seeding date had a greater effect than seeding rate on forage yield and quality. Highly productive switchgrass stands were obtained during the establishment year with mid-April to early-May seeding dates at rates of only 3.4 kg PLS ha <sup>-1</sup> when atrazine was used for weed control.	Iowa	Vassey et al. (1985)
Big bluestem, switchgrass	107–430 PLS m <sup>-2</sup>	100–200 PLS m <sup>-2</sup>	When atrazine is used as pre-emergence herbicide, seeding rates greater than 200 PLS m <sup>-2</sup> of switchgrass and big bluestem are not necessary for obtaining adequate stands, and lower rates may be sufficient in many years, especially for conservation plantings.	Nebraska	Vogel (1987)

<sup>1</sup>Abbreviations: PLS, pure live seed; DM, dry matter; CP, crude protein; DOM, digestible organic matter.

The primary goal of any seeding is to achieve a minimum plant population that will result in a productive stand or, at least, a stand able to fulfill the purpose for which it was planted. Recommended seeding rates usually exceed the minimum desired plant population, to allow a safety margin because all seed will not emerge as seedlings. Many studies demonstrate, however, that there is rarely any sustained benefit to increasing seeding rates above the documented recommended range (Table 2.7). There may be an initial yield or quality response to higher seeding rates, but this advantage is short-lived (rarely exceeding 1 yr) and cost associated with the higher seeding rate is rarely justified.

There have been a number of studies aimed at defining the best species and the optimal seeding rates for companion crops used during the establishment of perennial species (Table 2.7). Many companion crops can also be used for grain production, and research has demonstrated that seeding rates of a companion crop should be lower than when planted for grain production to avoid excessive competition, especially for light, with the weaker perennial species. In contrast, in the rare case these companion (annual) crops are

planted as monocultures, the optimal seeding rate for forage production is usually higher than when it is sown for grain production because the purpose is a rapid cover of leaf mass rather than the grain (Bishnoi, 1980).

Sometimes seeding-rate recommendations are increased based on planting method or conditions. For example, a Texas study found that Illinois bundleflower broadcast into a grass sod required twice the seeding rate to achieve the same seedling density as for drilling (Dovel et al., 1990). In most cases, the better option is to use the best seeding method and management rather than attempting to overcome adverse establishment methods or conditions with increased seeding rates.

### Conclusion—Rates of Seeding

The Code 512 General Criteria specify recommendations for planting rates obtained from the plant materials program, land grant and research institutions, extension agencies, or agency field trials. This section summarized 25 articles and found no benefits for seeding rates higher than those recommended by state agencies. Seed size varies among species and cultivars, and seeding rate should be adjusted to deliver seed on a PLS basis.

## PLANTING DEPTH

Proper planting depth is one of the critical factors determining success of a grassland planting. Utilizing the proper depth will maximize emergence and seedling growth to allow quicker establishment. Seed of forage species are typically smaller than most grain crops and, additionally, have a large range of seed shapes and sizes, so planting equipment should be adjusted to seed at the appropriate depth. We summarized 30 articles and found no evidence that planting depth should vary depending on the eventual purpose for the seeding.

### Establishment From Seed

Successful establishment is dependent upon placement of seed in a favorable environment for germination and subsequent emergence (Tables 2.8 and 2.9). The ideal planting depth depends on seed size, soil texture, soil moisture availability, time of seeding, and firmness of the seedbed. The most important consideration for determining planting depth of a given species is seed size. In general, larger seed can emerge from greater depths. There is a trade-off between increased water availability at greater soil depths, especially in arid environments, and the ability of seedlings to emerge from lower depths (Townsend, 1979). A general rule of thumb is that seed should not be planted deeper than seven times its diameter, with the optimum depth being four to seven times the diameter (Masters et al., 2004).

Even within a species, variation in seed size can affect the ideal planting depth. In Wyoming, the smaller alfalfa seed germinated and emerged better from 0.6 cm, whereas larger seeds benefit from the deeper placement (Erickson, 1946). This same study also found that alfalfa seed size was more important than planting depths between 0.6 and 1.7 cm. A common problem in arid environments is shallow and soil surface planting which causes seedlings to desiccate and die before becoming established (Cosgrove and Collins, 2003), because bare surfaces lose water more rapidly than when protected by litter (Winkel et al., 1991). However, extremely small seeds may be an exception because their emergence seems to be optimal when placed on the soil surface (Cox and Martin, 1984), and seedling

vigor can be compromised by deeper plantings (Tischler and Voigt, 1983).

Planting depth should vary with soil texture (Aiken and Springer, 1995). As a general rule, small seeded species should be planted slightly deeper in sandy soils (1.2–2.5 cm) compared to loam or clay loam soils (0.6–1.2 cm). Bermudagrass is very small seeded, and its recommended planting depth is 0–1.3 cm (Taliaferro et al., 2004), with an optimal depth of 0.6 cm (Keeley and Thullen, 1989). Proper seed placement is difficult to regulate unless the seedbed is firm to prevent seeding too deep (Masters et al., 2004). Typically seed should be covered with enough soil to maintain moist conditions for germination, but not so deep that the shoot cannot reach the surface (Zhang and Maun, 1990; Roundy et al., 1993; Cosgrove and Collins, 2003). Moisture conditions at planting and the subsequent precipitation were the most important factors affecting successful establishment (Townsend, 1979).

Establishment success will also vary with the degree of soil compaction, partly because compaction improves the capillary flow of water to the seed and seedling, yet too much compaction restricts the ability of seedlings and their roots to penetrate through the soil. Soil moisture near the surface increased as compaction increased from 0 to 83 kPa (0–12 psi) and was positively related to the emergence percentage of alfalfa seed (Triplett and Tesar, 1960). Conversely, switchgrass was able to germinate and emerge from 8 cm in loose soil, but only 10% of seeds emerged when compaction was 6.9 kPa (1 psi) and no seedlings emerged with pressure of 69 kPa (10 psi) (Hudspeth and Taylor, 1961). In addition to moisture, soil compaction also affects oxygen diffusion, soil temperature, and light penetration, all of which influence germination and emergence (Hudspeth and Taylor, 1961). In some species, the red:far red ratio of light that penetrates through the soil can regulate seed dormancy; however, this has not been well documented for forage seed (Cornaglia et al., 2009).

### Vegetative Establishment

Hybrid bermudagrass is typically planted as sprigs, which are vegetative propagules



The most important consideration for determining planting depth of a given species is seed size”

**TABLE 2.8.** Summary of published literature on planting depth for legume species, environment, and soil type.

Species and cultivar (if stated)	Environment <sup>1</sup>	State	Soil type(s)	Planting depth		Reference
				Tested	Optimum	
				cm		
Alfalfa 'Vernal', 'Ranger'	G/F1	Iowa	Webster silty clay loam	1.3, 2.5, 3.8	1.3	Beveridge and Wilsie (1959)
Alfalfa 'Vernal'	F2	Michigan	Conover silt loam, Hillsdale sandy loam	0, 0.6, 1.3, 2.5	1.3	Triplett and Tesar (1960)
Alfalfa 'Vernal', 'Ranger'	G/F1	Iowa	Webster silty clay loam	1.3, 2.5, 3.8	1.3	Beveridge and Wilsie (1959)
Alfalfa	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Alfalfa 'Grimm'	G/F1	Minnesota	Carrington, Clinton, Clarion silt loams, Merrimac loamy sand	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)
Falcata alfalfa 'Baker'	F3	Colorado	Vona sandy loam	1.3, 2.5, 3.8	1.3	Townsend (1992)
Alsike clover	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Arrowleaf clover 'Yuchi'	F4	Texas	Norwood fine sandy loam	0, 1.0, 2.5, 4.0	1.3	Rich et al. (1983)
Birdsfoot trefoil 'Empire' 'Viking'	G	Kansas	Unknown soil	1.3, 2.5, 3.8	1.3	Stickler and Wassom (1963)
Cicer milkvetch 'Lutana'	F3	Colorado	Nunn clay loam	1.3, 2.5, 3.8	1.3–2.5	Townsend (1979)
Crimson clover	G	Tennessee	Cumberland silt loam	0.6, 1.3, 2.5, 3.8	0.6–1.3	Moore (1943)
Striate lespedeza,	G	Tennessee	Cumberland silt loam	0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Korean lespedeza	G	Tennessee	Cumberland silt loam	0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Sericea lespedeza	G	Tennessee	Cumberland silt loam	0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Sericea lespedeza 'Serala 76'	F1	Alabama	Hiwassee sandy loam	1, 3	1.0–3.0	Qiu and Mosjidis (1993)
Red clover	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Red clover	G/F1	Minnesota	Merrimac loamy sand	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)
Sweetclover 'Madrid'	F5	Montana	Unknown sandy loam	0, 0.6, 1.3, 2.5, 3.8, 5.1 ,6.4, 7.6	0.6–5.1	Gomm (1964)
Sweetclover	G/F1	Minnesota	Carrington, Clinton, Clarion silt loams, Merrimac loamy sand	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)
Sweetclover, white	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Sweetclover, yellow 'Madrid'	F1	Nebraska	Sharpsburg silty clay loam	1.9, 3.8, 5.7	1.9	Haskins and Gorz (1975)
Sweetclover, yellow	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–2.5	Moore (1943)

TABLE 2.8. continued.

Species and cultivar (if stated)	Environment <sup>1</sup>	State	Soil type(s)	Planting depth		Reference
				Tested	Optimum	
				cm		
Woollypod vetch 'Lana'	G	California	Unknown sand	1.0, 5.0, 10.0, 15.0	1–15	Williams (1967)
White clover	G/F1	Minnesota	Carrington, Clinton, Clarion silt loams, Merrimac loamy sand	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)

G, Greenhouse; F1, Field - natural rainfall; F2, Field - irrigated at planting; F3, Field - irrigated; F4, Field - 129–256 mm irrigation at 28 d; F5, Field - 304–406 mm irrigation

comprised of tillers, rhizomes, or stolons. Research from the 1950s is still relevant and recommendations have remained unchanged. Sprigs should generally be planted 3–5 cm deep into moist soil (Taliaferro et al., 2004). Chiles et al. (1966) reported a decrease in sprig emergence as depth increased from 2.5 cm to 10 cm, with 'Greenfield', 'Midland', and 'Coastal' bermudagrass. 'Coastal' was negatively affected by planting deeper than 5.1 cm. Under dryland conditions, sprigs should be planted 5.1–6.4 cm deep; if irrigated, sprigs should be planted 3.8–5.1 cm deep (Stichler and Bade, 1996). Some newer hybrids, such as 'Jiggs' and 'Tifton 85', can also be planted using "tops" which are stolons or aboveground stems. For a "top" to take root, it must be mature, at least 6 wk old, and have six or more nodes (Stichler and Bade, 1996).

The biomass species miscanthus and giant reed are sterile and can only be established vegetatively from rhizomes or stems (Huisman and Kortleve, 1994; Decruyenaere and Holt, 2001). Most research plantings have been done by hand; however, commercial planting of rhizomes and stems can be done with the use of adaptations of existing equipment, such as potato or bulb planters.

### Conclusion—Planting Depth

The General Criteria of Code 512 specify planting at a depth appropriate for the seed size or plant material while assuring uniform contact with soil. We summarized 30 articles that overwhelmingly supported the specification of planting at the proper depth to achieve the purpose of successful establishment of forage and biomass. Generally, small seeds should be planted near the soil surface and larger seeds should be

planted deeper to ensure adequate coverage by the soil. A good guide is to plant seed no deeper than seven times the seed diameter.

Operation and Maintenance specifications of Code 512 recommend that the operator will inspect and calibrate equipment to ensure proper rate and depth of planting material. Recalibration will be required when changing the species, or perhaps even cultivars, because seed sizes vary.

### PROTECTION OF PLANTINGS—POSTSEEDING MANAGEMENT

During the period between seedling emergence and utilization for the intended purpose, a new pasture can be mowed or grazed to reduce weed competition and water requirements, and thus enhance its establishment. Mowing or grazing reduce competition from weeds on the desirable species and allow the stand density to increase by tillering. Conversely, the risk of mowing or grazing too early is that the stand can thin from plants destroyed by the physical disturbance from mowing or 'pulling' during grazing. One anecdotal guideline is to use the "pull" test to ensure that seedling roots are sufficiently developed to withstand grazing. In this section, we discuss postseeding mowing and grazing management during establishment.

Almost all research on postseeding management has been on grasslands that are intended for livestock and/or hay production. There is little information on the postseeding management of grasslands intended for erosion control,

**TABLE 2.9.** Summary of published literature on planting depth for grass species, environment, and soil type.

Species (and cultivar if stated)	Environment <sup>1</sup>	State	Soil type(s)	Planting depth		Reference
				Tested	Optimum	
				cm		
Bromegrass ‘Gala’	G/F1	Pennsylvania	Hagerstown silt loam	1.0, 3.0, 6.0	1–3	Sanderson and Elwinger (2004)
Buffelgrass	G	Texas	Hildago sandy clay loam	0, 0.6, 1.2, 2.4	0.6–1.2	Mutz and Scifres (1975)
Buffelgrass	G	Texas	Clareville clay loam	0, 0.6, 1.2, 2.4	0.6–1.2	Mutz and Scifres (1975)
Buffelgrass	G	Texas	Victoria clay	0, 0.6, 1.2, 2.4	0.6	Mutz and Scifres (1975)
Eastern gamagrass ‘Pete’	F1	Iowa	Canistio silty clay loam	2.5, 5.0	2.5–5.0	Aberle et al. (2003)
Kleingrass ‘Selection 75’	G	Texas	Valera clay	1, 2, 4, 4, 6, 8	0–6	Tischler and Voight (1983)
Orchardgrass ‘Dawn’ ‘Pennlate’	G/F1	Pennsylvania	Hagerstown silt loam	1.0, 3.0, 6.0	1–3	Sanderson and Elwinger (2004)
Orchardgrass	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–2.5	Moore (1943)
Perennial ryegrass ‘Madera’ ‘Mongita’ ‘Moranda’	G/F1	Pennsylvania	Hagerstown silt loam	1.0, 3.0, 6.0	1–3	Sanderson and Elwinger (2004)
Prairiegrass (rescuegrass) ‘Matua’	G/F1	Pennsylvania	Hagerstown silt loam	1.0, 3.0, 6.0	1–3	Sanderson and Elwinger (2004)
Smooth bromegrass ‘Lincoln’	G	North Dakota	Lihen sandy loam	0.6, 2.6, 5.1, 7.6, 10.2	2.6	Ries and Hofmann (1995)
Reed canarygrass	G/F1	Minnesota	Carrington, Clinton, Clarion silt loams, Merrimac loamy sand	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)
Smooth bromegrass ‘Lincoln’	F1	Nebraska	Kennebec silt loam	1.5, 3.0, 4.5, 6.0	1.5	Newman and Moser (1988)
Sudangrass	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5, 3.8, 5.1	0.6–5.1	Moore (1943)
Sudangrass	G	Tennessee	Cumberland silt loam	2.5, 5.1, 7.6, 10.2	2.5–5.1	Moore (1943)
Switchgrass ‘Alamo’	G	Alabama	Unknown loamy sand	0, 0.5, 1.0, 1.5, 2, 2.5	0.5–2.5	Miller and Owsley (1994)
Switchgrass ‘Alamo’	G	Alabama	Unknown clay loam	0, 0.5, 1.0, 1.5, 2, 2.5	1.0	Miller and Owsley (1994)
Switchgrass ‘Blackwell’	F4	Texas	Pullman clay loam	0.6, 1.3, 3.8, 6.4	0.6–1.3	Hudspeth and Taylor (1961)
Switchgrass ‘Pathfinder’ ‘Trailblazer’	F1	Nebraska	Kennebec silt loam	1.5, 3.0, 4.5, 6.0	1.5–3	Newman and Moser (1988)
Switchgrass–local ecotype	G	Canada	Unknown sand	0, 2, 4, 6, 8, 10, 12, 14, 16	2–8	Zhang and Maun (1990)
Tall fescue ‘KY31’	G	Oklahoma	Unknown sandy loam	1.3, 2.5, 3.8, 5.1	0.6–3.8	Walker et al. (2001)

TABLE 2.9. continued.

Species (and cultivar if stated)	Environment <sup>1</sup>	State	Soil type(s)	Planting depth		Reference
				Tested	Optimum	
				cm		
Tef-VNS	G	Kansas	Keith silt loam	0, 0.6, 1.3, 2.5, 5	0.6–1.3	Evert et al. (2009)
Timothy	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Timothy	G/F1	Minnesota	Carrington, Clinton, Clarion silt loams	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)
Timothy	G/F1	Minnesota	Merrimac loamy sand	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)

<sup>1</sup>G, Greenhouse; F1, Field - natural rainfall; F4, Field - 129–256 mm irrigation at 28 d.

biomass, or wildlife. These latter uses are also probably optimized by successful and rapid establishment so postseeding management is likely to be similar for all purposes. Regardless of the final use, during this part of the establishment period there is continued risk for environmental degradation.

Recommendations for postharvest management vary with factors such as seeding date, location, and seeding mixture. One detailed study on spring-seeded alfalfa in Minnesota found that under optimal conditions, seeding year yield was maximized when the initial harvest was made 60 d after spring emergence (compared with 40 d or 80 d) followed by two or three subsequent harvests (Sheaffer, 1983). The harvest schedules that resulted in the greatest total season yield varied among locations and years. In Wisconsin, an annual ryegrass companion crop harvested 60 d after spring planting (and subsequent harvests at 33-d intervals) reduced alfalfa yield and stand density compared with delaying the initial harvest until 67 d or 80 d (Sulc et al., 1993a).

Grazing during establishment to reduce competition depends on site-specific conditions. Contrary to the recommendation at that time of not grazing new stands of crested wheatgrass during the seeding year, Hull (1944) found that under ideal conditions in Idaho, moderate grazing may be practiced. Without herbicide use grazing is necessary for establishment of seedlings when seed is broadcast or no-till drilled into established stands (Barker and Dymock, 1993). Existing

vegetation needs to be controlled by regular mowing or grazing to reduce competition and allow light to the establishing seedlings.

In Florida, grazing to 7.5 cm resulted in a greater contribution from joint vetch that had been broadcast into limpgrass pasture, compared to grazing to 15 cm (Sollenberger et al., 1987). In a species-poor permanent grassland in Germany, forbs were broadcast seeded to increase species diversity and nutritive value (Hofmann and Isselstein, 2005). In that study, the best results were from mowing nine times before the spring seeding at weekly intervals to simulate grazing, and then every 3 wk after seeding. This carried over to the second year where the addition of forbs increased long-term yield, but the frequent cutting had a negative effect on total yield.

### Conclusion—Postseeding Management

In the General Criteria, Code 512 specifies that livestock shall be excluded until the plants are well established. This is not supported by the literature as grazing can be an effective method of vegetation control during establishment. We summarized six articles that compared postseeding management treatments, and there was consensus for site- and species-specific management in the year of planting. There is evidence of benefits from some mowing and/or grazing to reduce competition from weeds or other forage plants during the establishment period that can allow increased tillering and root growth to improve establishment success. One guideline is to use the “pull” test to ensure that seedling roots are



Options for weed control include mowing, grazing, companion crops, and chemical control.”

sufficiently developed to withstand modest grazing.

### PROTECTION OF PLANTINGS—WEED MANAGEMENT

The primary benefit of weed control is to enhance the establishment of the sown species, and minimize competition from nonsown species in the resultant stand (Barker et al., 1988). Options for weed control include mowing, grazing, companion crops, and chemical control.

Most research on weed control during establishment has been for grasslands for which production is the goal. We did not find any literature comparing weed control practices during establishment for those being established for purposes such as erosion control, C sequestration, wildlife, or biomass production. Intuitively, they are probably similar to that for production. However, some options, such as herbicides, are not acceptable for establishing forages for organic production.

#### Mowing

Mowing for weed control in forages is generally not very effective (Miller and Strizke, 1995) because it is nonselective and may occur too late to reduce competition between weeds and the seedlings. Late mowing may remove the tops of legume seedlings forcing the young seedlings to regrow from the base. And, if late, the greater amount of residue remaining on the field may continue to shade the seedlings. However, mowing can prevent weeds from going to seed and contributing to the soil seed bank. It is sometimes the best option to suppress grassy weeds, especially when trying to establish perennial grass species in grass–legume mixtures where no herbicides are approved.

#### Mob Grazing

Mob grazing is stocking a high density of animals in an area for a short duration (up to 1 wk). It reduces selective grazing by livestock to some extent, and thus can be effective in the control of grass weeds and allowing sunlight to the new seedlings (Miller and Strizke, 1995). In addition, the grazed material is removed from the area and no longer shades. However, grazing must be delayed until seedling roots are well established or the seedlings can be

uprooted. Often, as with mowing, the efficacy of mob-grazing is only moderate, because it is applied too late to have maximum benefit in reducing weed competition for moisture, sunlight, and nutrients, and damage to the soil from foot traffic may be significant. Further, unpalatable weeds might not be grazed and the young forage seedlings may be preferred to weed species.

#### Companion Crops

Companion crops such as annual ryegrass, oats, rye or triticale are sometimes seeded at reduced rates and used with spring-seeded alfalfa in northern latitudes to provide quicker ground cover, help reduce wind and water erosion, and deter weed growth during forage establishment (Kust, 1968; Schmid and Behrens, 1972; Chapko et al., 1991; Becker et al., 1998; Jefferson et al., 2005). Use of companion crops should be based on site-specific conditions such as erosion potential and forage needs during the establishment year (Hoy et al., 2002). However, shade from companion crops can also reduce alfalfa establishment and yield (Lanini et al., 1991), especially in southern latitudes where alfalfa is seeded in the fall. Hall et al. (1995) reported pre- and postemergence herbicides provided better weed control and higher forage yields than a companion crop; thus herbicides are generally replacing companion crops for weed suppression for monocultures (Brothers et al., 1994), except on organic plantings.

#### Chemical Weed Control

Most research on weed control in pastures has been with fully established pastures (NRCS Conservation Practice Standard, Herbaceous Weed Control, Code 315), which are not discussed in this section. Most references citing effects of chemical weed control during establishment are on monocultures, mainly for spring seedings of alfalfa and some perennial warm-season grasses. Cool-season grasses are usually seeded in fall and few herbicides are registered for use on grass–legume mixtures. Therefore, this literature synthesis and discussion of weed control options draws on the research implicit for the chemical labels in addition to refereed journal articles. Data from industry for registration is thoroughly reviewed for authenticity and should be reliable. As a caution, however, full herbicide labels change and the current label is the only reliable or legal

reference for use at a specific location or on a specific crop.

The point at which grassland is legally considered established for the purpose of herbicides use for pastures is usually defined in the label by the number of leaves. For labeling purposes, a grass seedling is usually *established* when it reaches the five-leaf stage. The 2,4-D amine and esters (Agri Star 2,4-D amine 4°, Anonymous, 2008c; Agri Star 2,4-D LV4 4°, Anonymous 2008d; Agri Star 2,4-D LV6°, Anonymous, 2008e) labels state they can be used on newly seeded grasses after the five-leaf stage. Likewise, the triasulfuron label (Amber°, Anonymous, 2006a) states that it can be used on newly established pastures for broadleaf weed control 60 d after emergence, which is approximately when perennial grass seedlings reach the five-leaf stage. Ries and Svejcar (1991) also reported that seedlings are considered established when seedlings form adventitious roots, which occurred between the four- and six-leaf stage in their study.

Frequently, weed control experiments report on formulations that are no longer registered (McMurphy, 1969; Fermanian et al., 1980; Bovey and Voigt, 1983; Bovey et al., 1986; Bovey and Hussey, 1991) or formulations that do not have approval for use on seedlings to be grazed (e.g., atrazine, bromoxynil, metribuzin, siduron, quinclorac, MSMA) (McMurphy, 1969; Peters and Lowance, 1970; Fermanian et al., 1980; Bovey and Voigt, 1983; Bovey et al., 1986; Bovey and Hussey, 1991). Other formulations are not labeled for the reported crop (e.g., imazethapyr, metolachlor; Griffin et al., 1988; Masters, 1997; Beran et al., 2000). In this review, care was taken to not include these experiments except for the effect of weed reduction at a certain growth stage on the establishment success.

Labels are often specific not only for the crop being treated, but for the management used, the weed problems, and the location, region, or state of the USA where it can be used. Aatrex° (atrazine; Anonymous, 2008a) is labeled only for CRP plantings and it is not approved for grazing, except for grazing sorghum–sudan grass hybrids. Quinclorac (Paramount°, Anonymous, 2008e) is labeled for grass seed production, but it is not approved for

grazing. Metolachlor (Dual II Magnum°, Anonymous, 2004a) has a 30-d grazing restriction in soybeans and a 120-d grazing restriction for pod crops such as peas and cowpeas. Imazethapyr (Pursuit°, Anonymous, 2008f or Thunder°, Anonymous, 2007b) is labeled for a number of forage legumes when used only as cover crops (i.e., alfalfa, birdsfoot trefoil, crownvetch, kudzu, lespedeza, lupin, milkvetch, sainfoin, velvet bean, and vetch), and has a 30-d grazing restriction for alfalfa and clovers. Bromoxynil (Buctril°, Anonymous, 2000a) has a 30-d grazing restriction for alfalfa, but is not labeled for other perennial legumes. In all cases, the current label is the only reliable guide.

A strategy for weed management during establishment must consider herbicide residues, primarily from the previous crop, especially when legumes follow grass crops and vice versa. Herbicide labels must be read carefully and planting restrictions must be followed. Soil tillage has commonly been used to reduce injury due to residual herbicide from a previous crop (Hall and Vough, 2007). There is also some potential for a negative environmental impact resulting from herbicide use. Excessive atrazine use and potential carryover can restrict the species options on treated land; however, any effect is likely to dissipate within 2 yr.

A cultivated seed bed before and after passage of a cultipacker-type seed drill. The front roller makes a shallow channel in which seed drops from a seed box; the back roller presses the seed into the soil and gives some soil coverage. Credit: David Barker, Ohio State University.



Other herbicides with potential mammalian toxicity (e.g., paraquat) have not been reported to have pronounced effects on nontarget species; however, this herbicide is being used less frequently than in previous years (Barker and Zhang, 1988). Some notorious negative effects of long-term use of agrichemicals on the environment have resulted in more carefully regulated use of these valuable tools.

### Hybrid Bermudagrass

The most effective herbicide to control small-seeded grasses and broadleaf weeds during bermudagrass establishment from sprigs is diuron (Direx®, Anonymous, 2003a), which can be applied immediately after sprigging, but before the new growth emerges. In addition, 2,4-D amine plus dicamba (Weedmaster®, Anonymous, 2008h), 2,4-D amine (Anonymous, 2008c), 2,4-D LV6 (Anonymous, 2008e), and 2,4-D acid plus dicamba acid (Outlaw®, Anonymous, 2003b) can be applied any time after sprigging to control small-seeded grasses such as crabgrass, if applied when crabgrass is germinating (within 10 d of planting), or to control emerged broadleaf weeds (Butler et al., 2006a, 2006b). Alternatively, 2,4-D amine

plus picloram (Grazon P+D®; Anonymous, 2009a) can be used on hybrid bermudagrass established by sprigging after stolons reach 15 cm.

### Seeded Native Warm-Season Perennial Grasses

For big bluestem, imazapic (Impose®, Anonymous, 2007a; Beran et al., 2000) can be applied prior to planting or after seedlings reach the five-leaf stage to control many annual grasses such as crabgrass, broadleaf signalgrass, fall panicum, Texas panicum, sandbur, yellow nutsedge, and seedling johnsongrass, which can be problematic weeds during establishment. Imazapic does not have a grazing restriction, but treated areas should not be cut for hay for at least 7 d after application. Big bluestem was successfully established with imazethapyr (Beran et al., 2000) and atrazine can be used on CRP plantings of big bluestem to improve establishment (Martin et al., 1982; Masters, 1995; Anonymous, 2008a). Hintz et al. (1998) reported that big bluestem could be successfully established with atrazine and corn as a companion crop, since it is labeled for corn. Areas treated with atrazine have



Alfalfa seedlings 4 mo after spring seeding in Ohio using a cultipacker-type seed drill seen in previous photo. Credit: David Barker, Ohio State University

a grazing restriction; however, this is not a major factor because new plantings of big bluestem should not be grazed during the establishment year.

Big bluestem has been reported to be tolerant to metolachlor (Griffin et al., 1988; Masters, 1997); however, it is not labeled for use in pastures. Metolachlor has a 30-d grazing restriction on soybean and a 120-d grazing restriction for pod crops such as peas and beans. Therefore, if big bluestem could be established with a companion crop, then the forage restriction of the primary crop (legume) could be followed to allow establishment of the companion crop. In noncrop areas, sulfosulfuron (Outrider®; Anonymous, 2004b) controls johnsongrass, yellow nutsedge, purple nutsedge, and tall fescue when applied to newly seeded big bluestem after the three-leaf stage; however, treated areas may not be grazed because sulfosulfuron is approved for grazing only in bermudagrass and bahiagrass pastures (Outrider® supplemental label; Anonymous, 2008b). In noncrop areas or where big bluestem is grown for seed production only, quinclorac plus methylated seed oil may be applied to control several annual grasses if the treated areas are not to be grazed.

For indiagrass, imazapic (Impose®; Anonymous, 2007a) can be applied prior to planting or after seedlings reach the five-leaf stage to control many annual grasses such as crabgrass, broadleaf signalgrass, fall panicum, Texas panicum, sandbur, yellow nutsedge, and seedling johnsongrass. On established plantings, imazapic does not have a grazing restriction, but treated areas should not be cut for hay for at least 7 d after application. In noncrop areas, sulfosulfuron (Outrider®; Anonymous, 2004b) controls johnsongrass, yellow nutsedge, purple nutsedge, and tall fescue when applied to newly seeded indiagrass after the three-leaf stage. However, treated areas may not be grazed during that season since sulfosulfuron is approved only for grazing in bermudagrass and bahiagrass pastures (Outrider® supplemental label; Anonymous, 2008d).

Switchgrass is categorized into upland and lowland ecotypes, which vary in their response

to herbicides and management. McMurphy (1969) reported that 1.6 kg siduron ha<sup>-1</sup> controlled crabgrass with no effect on ‘Caddo’ upland switchgrass. However, Bovey and Hussey (1991) reported excessive injury to ‘Alamo’ lowland switchgrass at 2.2 kg siduron ha<sup>-1</sup>. ‘Pathfinder’ upland switchgrass tolerated pre-emergent applications of atrazine, which greatly improved establishment (Martin et al., 1982; Vogel, 1987; Masters et al., 1996; Hintz et al., 1998). McKenna et al. (1991) reported that ‘Pathfinder’ upland switchgrass injury increased as the rate of atrazine increased from 1.1 to 2.2 kg ha<sup>-1</sup>. Atrazine suppressed the growth of ‘Pathfinder’ upland switchgrass and injury was greater on a sandy loam soil compared to a silty clay loam soil (Bahler et al., 1984). Upland switchgrass could be established with atrazine with corn used as a companion crop, because it is labeled for corn (Hintz et al., 1998).

Atrazine at 1.1 kg ha<sup>-1</sup> can cause excessive injury to lowland ‘Alamo’ switchgrass and should not be used (Bovey and Hussey, 1991), whereas upland ‘Cave in Rock’ switchgrass tolerated this rate. Rainfall immediately after planting may reduce atrazine activity on lowland switchgrass. In one year, rainfall occurred the day after treating with atrazine and the lowland switchgrass was killed. In the second year rainfall did not occur for 2 wk after treatment and the lowland switchgrass had only transient injury (T. J. Butler, unpublished data). Imazethapyr was a viable replacement option for atrazine when big bluestem was being established, but not for ‘Trailblazer’ upland switchgrass, because results were not consistent across locations (Masters et al., 1996).

In noncrop areas, sulfosulfuron (Outrider®; Anonymous, 2004b) controls johnsongrass, yellow nutsedge, purple nutsedge, and tall fescue when applied to newly seeded switchgrass after the three-leaf stage; however, treated areas may not be grazed, because sulfosulfuron is approved for grazing of only bermudagrass and bahiagrass pastures (Outrider® supplemental label; Anonymous, 2008d). In noncrop areas or switchgrass grown for seed production only, quinclorac (Paramount®, Anonymous, 2008e) plus methylated seed oil may be applied to control



Switchgrass is categorized into upland and lowland ecotypes, which vary in their response to herbicides and management.”



There are several herbicide options for establishing alfalfa”

seedlings of several annual grasses, if the treated areas are not to be grazed.

The quinclorac label will likely be expanded to include switchgrass grown for biofuel. Already, nicosulfuron has received a 24(c) special local need label in Tennessee to control certain annual grasses and johnsongrass after the switchgrass has reached two-leaf stage (Accent®, Anonymous, 2008b). Other states will likely be added to the 24(c) label if switchgrass is grown for biofuel and the treated areas are not grazed.

Griffin et al. (1988) reported that NA (1,8-naphthalic anhydride) improved resistance of switchgrass seedlings to metolachlor; however, there has been relatively little research evaluating seed safeners to improve forage establishment (Roder et al., 1987). Based on the literature, most herbicide recommendations for establishing switchgrass are unreliable, especially for lowland ecotypes.

### Introduced Warm-Season Grasses

Weed control greatly increased the success of establishment in seeded bermudagrass (Fermanian et al., 1980), weeping lovegrass (Bovey and Voigt, 1983), and buffelgrass, kleingrass, Wilman lovegrass, WW Ironmaster, and WW Spar Old World Bluestem (Bovey et al., 1986; Bovey and Hussey, 1991). But none of the herbicides evaluated has been registered or approved for grazing, so these studies are not discussed.

### Cool-Season Perennial Grasses

Only a few studies of herbicide use during establishment of cool-season perennial grasses are reported in the literature. Most herbicides used for establishing small grains or warm-season perennial grasses listed above are detrimental to establishment of cool-season grasses (T. J. Butler, unpublished data). In the Southern Great Plains, successful establishment of tall fescue, tall wheatgrass, and experimental hardinggrass across multiple environments could be achieved by sequentially 1) spraying glyphosate in the spring to eliminate seed production from winter annual grasses prior to the autumn planting, b) delaying seeding (with a drill) until autumn rainfall and emergence of winter annual grasses has occurred, and

c) following immediately with another application of glyphosate to control emerged weeds (Butler et al., 2008). This method is also recommended for the Pacific Northwest, but production from the fields is lost for the preceding summer (Thompson, 1970).

### Legumes

**Alfalfa.** There are several herbicide options for establishing alfalfa (Mueller-Warrant and Koch, 1983) some of which may also be used on other legumes (listed in Table 2.10). Although herbicides can give good weed control, the response might not always increase yield or be economic (Hall et al., 1995). Treflan is generally the preferred choice among pre-emergent herbicides, because the cost is significantly lower than alternatives (Anonymous 2008g). Benefin, EPTC, and trifluralin may be incorporated prior to planting to control grass weeds primarily.

Pendamehalin may be applied to the soil after alfalfa reaches the two-leaf stage; however, it must be activated by rain or irrigation to control weeds as they germinate and it does not have any postemergent activity. The herbicide 2,4-DB may be applied to very small broadleaf weeds that are actively growing once alfalfa reaches the two-leaf stage. Bromoxynil will control several broadleaf weeds after alfalfa reaches the four-leaf stage, but like 2,4-DB, bromoxynil will not control grassy weeds. Imazethapyr may be applied to alfalfa after it reaches the two-leaf stage to control both grass and broadleaf weeds that are very small, and it also provides residual weed control. Imazamox can be applied after alfalfa reaches the two-leaf stage to control certain broadleaf and primarily grassy weeds. It tends to have more grass activity than imazethapyr, but it has less residual activity. Clethodim and sethoxydim will control grassy weeds, but not broadleaf weeds. Recommended tank mixes for the simultaneous application of two herbicides (e.g., to control both grasses and broadleaf weeds) are specified in the full versions of herbicide labels.

Roundup Ready® Alfalfa. Following its initial release in 2005, Roundup Ready® (i.e., glyphosate-tolerant) alfalfa was removed from commercial sale during 2007–2010 for additional environmental testing. It was

**TABLE 2.10.** Herbicides labeled for alfalfa along with conventional use rates, applications timings, grazing or harvest restrictions, and other forage legumes listed on the label.

Active ingredient	Rate	Timing	Harvest restriction	Other legumes <sup>1</sup>
	ha <sup>-1</sup>		d	
Preplant, incorporated				
Benefin	2.24 kg	Preplant, incorporated	–	C, BT
EPTC	7.0 L	Preplant, incorporated	14	C, BT, L
Trifluralin	1.17 L	Preplant, incorporated	21	
Seedling stage				
Bromoxynil	1.8 L	> Four leaf	30	
2,4-DB	4.68 L	Two–four leaf	60	RC, WC, BT
Pronamide	1.68 kg	> One leaf	25	C, CV, S
Imazethapyr	0.2–0.4 L	> Two leaf	30	C, FP,
Sethoxydim	2.3 L (annuals) 4.3 L (perennials)	Early postseeding	14	C, BT, S
Pendimethalin	2.3 L	> Two-leaf alfalfa, prior to weeds	50	
Imazamox	0.3 L	> Two leaf	20	FP, CP
Clethodim	0.6 L (annuals)	Early postseeding	15	C, BT, S
	1.2 L (perennials)			
Established stands (in addition to seedling stage)				
Flumioxazin	0.3 L	< 15 cm alfalfa, prior to weeds	25	
Paraquat	0.9 L	Postseeding	30	
Pendamethalin	4.7 L	< 15 cm alfalfa, prior to weeds	50	
Norflurazon	0.5–2.8 L	> 5 mo alfalfa, prior to weeds	28	
Trifluralin	2.3–4.6 L	Prior to weeds	21	
Dormant				
Paraquat	1.8 L	> 1 yr, dormant	60	
Diuron	2.8 L	> 1 yr, dormant	70	BT, RC, FP
Pronamide	2.2 kg	Dormant (< 12°C)	25	
Terbacil	1.7 kg	Dormant	–	
Metribuzin	2.3 L	> 1 yr, dormant	28	S
Hexazinone	4.7 L	> 1 yr, dormant	30	

<sup>1</sup>BT, birdsfoot trefoil; C, clovers not specified; CP, cowpea; CV, crownvetch; FP, field pea; L, lespedeza; RC, red clover; S, sainfoin; WC, white clover.

released from USDA regulation and became available commercially in January 2011. Glyphosate (Anonymous, 2005a) may be applied at 0.84–1.68 kg ae ha<sup>-1</sup> (22–44 fl oz ac<sup>-1</sup>) from the time of emergence until 5 d prior to first cutting to control many broadleaf and grass weeds, especially perennial weeds that most conventional herbicides do not control. No yield reduction of alfalfa occurred when glyphosate was applied up to 3.36 kg ae ha<sup>-1</sup>, which is four times the normal rate (Steckel et al., 2007). No differences in establishment or yield were found

between Roundup Ready® alfalfa treated with glyphosate and a conventional alfalfa treated with imazamox (Sheaffer et al., 2007). However, Roundup Ready® systems with glyphosate provided more consistent weed control and less injury to the alfalfa compared with the conventional system with imazamox (McCordick et al., 2008). In addition, the conventional herbicides imazamox and imazethapyr caused minor alfalfa injury and 2,4-DB and bromoxynil further decreased crop safety compared to glyphosate (Wilson and Burgener, 2009).

**TABLE 2.11.** Summary of purposes, criteria used for evaluation, and level of research support of NRCS Conservation Practice Standard, Forage and Biomass Planting, Code 512.

Purposes of the Practice Standard	Criteria used for assessing achievement of purpose	Support by research based on 363 scientific publications and 162 species
Improve or maintain livestock nutrition and health	· By establishing species and cultivars with greater production, and potential to increase animal intake	· Species and cultivars differ in production and quality. But increased livestock production was assumed more likely from increased stocking rate than intake per head.
	· By establishing species and cultivars with greater nutritive value (i.e., energy content, protein or mineral concentration)	· A negative relationship often occurs between production and nutritive value. Less productive species and cultivars (above) can have higher nutritive value.
	· By replacing species with low nutritive value or with high levels of toxic compounds	· Whether through complete stand replacement (e.g., full cultivation) or partial stand replacement (e.g., sod- or no-till seeding), species with greater nutritive value can be introduced into grasslands.
	· By establishing species and cultivars to provide nutrition during periods of feed deficit (e.g., extend forage production season)	· Species and cultivars that are tolerant to cold can improve early-spring and late-autumn production, and those tolerant to heat and drought can improve summer production. Major species are well characterized in the scientific literature.
	· By establishing species with wildlife benefits such as nesting habitat, cover, biodiversity, and insects	· Wildlife species vary in nutritional and habitat requirements that are not met by any single forage species. Species-rich vegetation offers more benefits to wildlife than monocultures.
Provide or increase forage supply during periods of low forage production	· By establishing species and cultivars with greater production potential	· More productive species and cultivars can be harvested for hay or silage, or for use during periods of low forage production.
	· By establishing species with higher environmental tolerance (e.g., cold, heat, drought, pH, salinity)	· Cold- and drought-tolerant species with greater forage production during feed-deficit periods can provide in situ grazing and reduce hay or silage feeding costs.
	· By establishing annual forage crops to fill predicted feed deficits for harvest or grazing	· Annual forage species can be planted into existing grassland or as cover crops in grain systems, to provide forage for in situ grazing or for hay or silage harvest.
Reduce soil erosion	· By establishing perennial species that provide year-round ground cover, and by avoiding cultivation	· Perennial grasslands have year-round soil cover with lower rates of soil loss than bare soil and can be managed for improved persistence.
	· By establishing species with improved adaptation and greater persistence	· Stand longevity of new alfalfa cultivars with multiple insect and disease resistance may be more than double that of older cultivars.
	· By using no-till methods for establishment to alleviate soil cultivation	· Sod- and no-till seeding, especially with herbicide use for vegetation control can successfully establish grasslands.
	· By establishing plants with greater ground cover that reduces the rate of surface water flow	· Plants with greater ground cover and denser vegetation have less runoff and higher water infiltration. Vegetation density is also affected by management.

Other Legumes. Arrowleaf clover was relatively tolerant to 2,4-DB, which was effective in controlling many broadleaf weeds when they are small and actively growing (Conrad and Stritzke, 1980). Both 2,4-DB and bromoxynil were safe on

Korean lespedeza, and 2,4-D amine only caused minor injury and provided better ragweed control (Peters and Lowance, 1970). Currently, 2,4-DB is labeled only for alfalfa and seedling birdsfoot trefoil; however, efforts are under way to include other legume species.

TABLE 2.11. continued.

Purposes of the Practice Standard	Criteria used for assessing achievement of purpose	Support by research based on 363 scientific publications and 162 species
Improve soil and water quality	· By establishing species with vigorous root growth that ensures carbon sequestration and nutrient uptake	· In general, grasses have dense, fibrous root systems while legume root systems may include large taproots and crowns; rooting characteristics are affected by management as well as establishment practices.
	· By establishing N-fixing legumes, thus reducing the need for fertilizer N	· Legumes are relatively fast to establish, can be included in grassland mixtures, or can be no-till drilled (sod-seeded) or broadcast seeded (frost-seeded) into grass stands
	· By establishing species that ensure efficient nutrient cycling, and support active populations of soil macro- and micro-organisms	· Nutrient cycling and some soil microbial processes are impaired during establishment, but resume once the stand is established. Later on, nutrient cycling is affected significantly by forage removal as hay or silage.
	· By reducing soil erosion	· Where water quality is a critical issue, new seedlings should use no-till methods or fast-establishing companion crops to avoid bare soil or reduce time of bare soil exposure.
Produce feedstock for biofuel or energy production	· By establishing species and cultivars with high biomass potential	· The most productive biofuel feedstocks (miscanthus and giant reed) can be established vegetatively with the use of stems and/or rhizomes. Switchgrass can be established from seed.
	· By establishing species and cultivars with unique characteristics for biofuel or energy production (e.g., low ash, high cellulose)	· Species differ in concentration and types of structural and nonstructural carbohydrates for biofuel purposes. Several forage species have high ash content and may be less suitable for biofuel purposes than others.

Imazethapyr improves establishment of tickclover, roundhead lespedeza, and leadplant better than imazapic, whereas crownvetch, partridgepea, purple prairie clover (Beran et al., 1999) and Illinois bundleflower (Masters et al., 1996; Beran et al., 2000) tolerated both imazapic and imazethapyr. Imazethapyr caused transient injury only to birdsfoot trefoil, cicer milkvetch, red clover, sainfoin, and yellow sweetclover, and did not reduce legume yield (Wilson, 1994). Imazapic is approved for grazing, whereas imazethapyr is approved only for alfalfa, clover, and field peas. Most forage legumes are not listed in the specimen label and there are no chemical weed control options for these crops. Interestingly, if these forage legumes were mixed at planting with alfalfa as a companion crop, then all the labeled herbicides for alfalfa establishment could be used legally, as long as the grazing restrictions were followed for alfalfa as the primary crop.

### Conclusion—Weed Management

The Code 512 General Criteria specify that invasion by undesirable plants shall be controlled by cutting, using a selective herbicide, or by grazing management by manipulating livestock type, stocking rates, density, and duration of stay. Insects and diseases shall be controlled when an infestation threatens stand survival. The literature strongly supports the statement that forage establishment is greatly improved when weeds are controlled. Generally, herbicides that selectively kill the undesirable herbaceous vegetation (even with minor crop injury) speed the rate and success of establishment compared to alternative methods, but may not be the most economic strategy. One area of deficiency in the literature is the quantified benefit of herbicide use for other conservation values. Implicitly, the faster a stand can be established to shorten the duration to utilization and lessen the risks of low ground cover, the greater its conservation value will be.



A seasonal, grazing dairy herd on endophyte-free tall fescue pasture in Ohio. Credit: David Barker, Ohio State University.

## CONCLUSIONS AND EMERGING ISSUES

Code 512 specifies practices for planting grasslands intended to 1) sustain livestock nutrition and health, 2) provide forage during periods of low supply, 3) reduce soil erosion, 4) improve soil and water quality, and 5) produce feedstock for bioindustrial purposes. The objective of this chapter was to evaluate the research to determine if it supports the purposes and criteria of the practices described in the Standard. We summarized 363 publications related to grassland establishment, and found a high degree of consensus between the recommended practices in the standard and the research literature (Table 2.11). Most of the basic principles are known, and local experts can fine-tune the recommendations to increase the chances for establishment success.

The literature was deficient in some areas of research. In general, past research has focused primarily on grass and legume establishment in support of livestock production, and primarily on a limited number of popular species. Specific emphasis has included total forage production (for grazing, hay, or silage), forage

quality, and to a lesser extent, the seasonality of production. Some forage literature addressed other ecosystem services (e.g., erosion, wildlife, water quality, carbon sequestration, and biofuels); however, this research was mainly conducted in mature pastures and hayfields, i.e., on the desired result, and rarely considered the establishment period.

In general, establishment practices are similar for all purposes for which a stand might be used. In cases where erosion and water quality are of special concern, establishment practices that avoid full cultivation are most likely justified, but there were no studies directed at this relationship. Further, it is not known if establishment practices differ in their effect on carbon sequestration; however, species selection and their postestablishment management can greatly influence the net carbon balance of a grassland system. This was very evident in the number of species evaluated in that several ‘minor’ species may be the best for delivery of priority environmental of ecosystem services with adequate, but not optimum production value (Table 2.11).

Researchers have a daunting task to describe interactions for all grassland species (162 in this chapter), in all topographies, for all climate zones within the USA, and for all the purposes for which these species can be used. To this extent, grassland establishment cannot be completely supported in all respects by research, and practitioners will be forced to extrapolate establishment guidelines to individual fields, producers, and purposes. In this respect, Code 512 is valid to recommend input from local plant materials programs, land grant and research institutions, extension agencies, or agency field trials. Even so, there is a need for modeling approaches to allow more effective transfer of technology and cost–benefit relationships to assist in decision making on species and establishment practices at the local level.

The scientific literature includes relatively little information on establishment failures, yet it is common knowledge that several systems tried did not work and were not published. One publication (Bartholomew, 2005) estimated that 7–55% of the cases resulted in failures of forage reseeds, and

recommends this cost be included in economic analyses. We have incomplete information on factors contributing to establishment failure, something that likely varies from location to location because of soil and climate, with amount of management input. If unsuccessful approaches were studied the scientists could learn and perhaps use the information to alter practices to overcome the problems, but without some basic information everyone begins with no information. This is especially critical because the variety of purposes emerging will demand data and recommendations on a greater variety of species than currently used for production.

Several emerging issues are likely to affect future forage establishment practices:

1. Roundup Ready® technology has been introduced to alfalfa, but the effect this technology might have on establishment practices is yet unknown. Emerging technologies take time to conduct the research to be published, and then the publication process may take an additional year or more.
2. The organic forage-based livestock industry has been growing at a steady rate in the USA (approx. 18% yr<sup>-1</sup>). The restriction on the use of agrichemicals and genetically modified plant species within these systems intensify the need for research on successful establishment practices for pastures and hayfields. Many organic plantings were established with conventional methods and transitioned into organic production, but new forage seedings will require establishment using organic principles including the use of seed grown organically.
3. New technologies (e.g., polymer seed coats, new rhizobium strains) are being developed that will improve seed longevity in storage, and improve establishment success.
4. New cultivars are continually being developed in most species used for production with faster and more uniform emergence characteristics.
5. Seed quality is being recognized as an important factor, and more specialized methods for production and storage are being developed.
6. New equipment for seeding to assure good soil–seed contact and improved pesticides will continue to be evaluated.
7. Hayfields and pastures will continue to occupy the most erosive land sites and global change and ecosystem expectations and regulations will gain emphasis.
8. More emphasis is needed on establishing principles of potential biofuel crops and those species that will improve grasslands for environmental and ecosystem services.
9. There is a strong need for modeling research to strengthen the interrelationships among principles to allow decision makers to evaluate species and establishment methods to most effectively meet the broader goals of the landowner.
10. There will be a greater need for monitoring to insure the practice implemented is working and will be successful. This will need to be linked with landowner education and enhanced ability to have adaptive management to steer the practice to success.

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## CHAPTER

# 3

# Prescribed Grazing on Pasturelands

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Sustainable grasslands enhance environmental quality and the resource base of the ecosystem while providing human food needs”

# Prescribed Grazing on Pasturelands

Lynn E. Sollenberger, Carmen T. Agouridis, Eric S. Vanzant,  
Alan J. Franzluebbers, and Lloyd B. Owens

## INTRODUCTION

Prescribed grazing is defined by the Natural Resources Conservation Service (NRCS) as “managing the harvest of vegetation with grazing and/or browsing animals” (NRCS, 2007). The principles of grazing management center round the temporal and spatial distribution of various kinds and number of livestock (Heitschmidt, 1988). Within the context of this chapter, management of grazing or browsing will be characterized in terms of intensity, method, and season (timing), and as a function of the type and class of livestock and their distribution on the landscape.

The choice to use a particular level of any of these management strategies should be objective driven. Objectives may include achieving canopy conditions and forage productivity that result in optimal levels of animal performance (Hodgson, 1990), but can be expanded to include the concept of sustainability and provision of ecosystem services. Sustainable grasslands enhance environmental quality and the resource base of the ecosystem while providing human food needs in a manner that is economically viable and that enhances the quality of life for both producers and consumers (Stewart et al., 1991). Achieving such a wide range of objectives is a challenge for those implementing and practicing prescribed grazing.

The NRCS has developed conservation practice standards to provide guidance for applying conservation technology on the land and to set the minimum acceptable level for application of the technology. The Prescribed Grazing Practice Standard (code 528; see Appendix I) is intended for application to all lands where grazing or browsing animals are managed. An assessment

of prescribed grazing purposes on rangeland has been completed (Briske et al., 2011), so this chapter is focused on the same purposes for pastureland. The five specific purposes outlined in the Prescribed Grazing Practice Standard for pastureland and the criteria by which they were assessed are summarized in Table 3.1.

The goal of this literature synthesis was to determine if the prescribed practices do, in fact, meet the purposes and criteria. Therefore, the assessment is organized around the five purposes (as main headings) or desired outcomes from imposing prescribed grazing “management strategies.” Management strategies include grazing intensity, stocking method, timing of grazing (i.e., season of grazing and deferment from grazing), type and class of livestock, and livestock distribution on the landscape.

A comprehensive search and review of the refereed literature was conducted for each management strategy to describe its effect on the grazing system and to determine if implementation of the strategy will achieve the short- and long-term purposes of the practice standard. Knowledge gaps in the literature were identified, and the potential use of management to correct undesirable trends or restore desired grassland condition was explored. The focus was U.S. literature, but in cases where U.S. data were unavailable or limited, international research and well-designed, nonrefereed papers were used.

## PURPOSE 1: IMPROVE OR MAINTAIN DESIRED SPECIES COMPOSITION AND VIGOR OF PLANT COMMUNITIES

### GRAZING INTENSITY

Measures of grazing intensity are animal or pasture based. Stocking rate (animal units  $\text{ha}^{-1}$ )



Rotational stocking used on a “Florakirk” bermudagrass pasture in Florida. Photo by Lynn Sollenberger, University of Florida.

**TABLE 3.1.** Purposes of the Prescribed Grazing Practice Standard, criteria for assessing achievement of the purposes, and a summary of which grazing strategies were documented in the literature to affect these criteria.

Purposes of the practice standard	Criteria for assessing achievement of the purpose	Level of research support (in parentheses) <sup>1</sup> of prescribed grazing strategies for each criterion
Improve or maintain desired species composition and vigor of plant communities	<ul style="list-style-type: none"> <li>· By providing grazed plants sufficient recovery time to meet objectives</li> <li>· By improving or maintaining vigor of plant communities, especially key species</li> <li>· By enhancing diversity of plants and optimizing delivery of nutrients to animals</li> <li>· By combining it with other pest management practices to promote community resistance to invasive weed species and enhance desired species</li> </ul>	<ul style="list-style-type: none"> <li>· Stocking method (SS); season of grazing (SS)</li> <li>· Grazing intensity (SS); stocking method (MS); season of grazing (MS); type and class of livestock (MS)</li> <li>· Grazing intensity (SS); stocking method (WS); distribution of livestock (MS)</li> <li>· Grazing intensity (SS); stocking method (MS); season of grazing (MS)</li> </ul>
Improve or maintain quantity and quality of forage for grazing and browsing animals' health and productivity	<ul style="list-style-type: none"> <li>· By reducing animal stress and death from toxic or poisonous plants</li> <li>· By improving and maintaining plant health and productivity</li> <li>· By basing management on target levels of forage utilization or stubble height as a tool to help insure goals are met</li> <li>· By locating of feeding, watering, and handling facilities to improve animal distribution</li> </ul>	<ul style="list-style-type: none"> <li>· None documented</li> <li>· Grazing intensity (SS); stocking method (MS); season of grazing (SS); type and class of livestock (MS)</li> <li>· Grazing intensity (SS)</li> <li>· Distribution of livestock in the landscape (MS)</li> </ul>
Improve or maintain surface and/or subsurface water quality and quantity, and riparian and watershed function	<ul style="list-style-type: none"> <li>· By improving or maintaining riparian and watershed function</li> <li>· By minimizing deposition or flow of animal wastes into water bodies</li> <li>· By minimizing animal effects on stream bank stability</li> <li>· By providing adequate litter, ground cover, and plant density to maintain or improve infiltration capacity of the vegetation</li> <li>· By providing ground cover and plant density to maintain or improve filtering capacity of the vegetation</li> <li>· By minimizing concentrated livestock areas, trailing and trampling to reduce soil compaction, excess runoff, and erosion</li> </ul>	<ul style="list-style-type: none"> <li>· Grazing intensity (SS); stocking method (MS); season of grazing (SS); distribution of livestock (MS)</li> <li>· Grazing intensity (SS); stocking method (WS); season of grazing (WS); distribution of livestock (SS)</li> <li>· Grazing intensity (WS); stocking method (MS); season of grazing (MS); distribution of livestock (SS)</li> <li>· Grazing intensity (SS); stocking method (MS); season of grazing (MS)</li> <li>· Grazing intensity (SS); stocking method (MS); season of grazing (MS)</li> <li>· Grazing intensity (SS); stocking method (MS); season of grazing (MS)</li> </ul>

is the most common animal-based measure of grazing intensity. Pasture- or sward-based measures include forage mass, canopy height, and canopy light interception. Forage allowance and grazing pressure include both a pasture and animal measure. These terms have been defined by the Forage and Grazing Terminology Committee (Allen et al., 2011).

It is suggested that the choice of grazing intensity is more important than any other single grazing management decision (Jones and Jones, 1997; Sollenberger and Newman, 2007) because of its prominent role in determining forage plant growth and persistence (Chacon and Stobbs, 1976), forage mass and allowance (Burns et al., 2002; Hernández Garay et al.,

TABLE 3.1. continued.

Purposes of the practice standard	Criteria for assessing achievement of the purpose	Level of research support (in parentheses) <sup>1</sup> of prescribed grazing strategies for each criterion
Reduce accelerated soil erosion, and maintain or improve soil condition	<ul style="list-style-type: none"> <li>· By reducing accelerated soil erosion</li> <li>· By minimizing concentrated livestock areas to enhance nutrient distribution and improve ground cover</li> <li>· By improving carbon sequestration in biomass and soils</li> <li>· By application of soil nutrients according to soil test to improve or maintain plant vigor</li> </ul>	<ul style="list-style-type: none"> <li>· Grazing intensity (MS)</li> <li>· Grazing intensity (MS); stocking method (MS)</li> <li>· Grazing intensity (MS)</li> <li>· Grazing intensity (MS)</li> </ul>
Improve or maintain the quantity and quality of food and/or cover available for wildlife	<ul style="list-style-type: none"> <li>· By maintaining adequate riparian community structure and function to sustain associated riparian, wetland, flood plain, and stream species</li> <li>· By providing for development and maintenance of the plant structure, density, and diversity needed for desired fish and wildlife species</li> <li>· By improving the use of the land for wildlife and recreation</li> <li>· By avoiding any adverse effects on endangered, threatened, and candidate species and their habitats</li> </ul>	<ul style="list-style-type: none"> <li>· Grazing intensity (SS); season of grazing (SS); distribution of livestock (MS)</li> <li>· Grazing intensity (SS); season of grazing (SS); type and class of livestock (MS); distribution of livestock (MS)</li> <li>· Grazing intensity (SS); season of grazing (MS); distribution of livestock (MS)</li> <li>· Grazing intensity (MS); season of grazing (MS); distribution of livestock (MS)</li> </ul>

<sup>1</sup>The five grazing strategies were grazing intensity, stocking method, season and deferment of grazing, type and class of livestock, and distribution of livestock in the landscape. SS indicates strongly supported; MS, moderately supported; and WS, weakly supported; for grazing strategies not shown there was no support in the literature that this strategy affected the criterion in question.

2004a), animal performance (Humphreys, 1991; Newman et al., 2002b), size of nutrient pools and fluxes between pools (Thomas, 1992; Dubeux et al., 2006), soil chemical and physical characteristics (Kelly, 1985; Dubeux et al., 2009), water quality (Van Poollen and Lacey, 1979), and profitability of the grazing operation. Understanding the relationships of grazing intensity with pasture, animal, and soil responses is crucial for the long-term success of the forage-livestock enterprise (Walker, 1995). In this section the focus is on plant responses to grazing intensity.

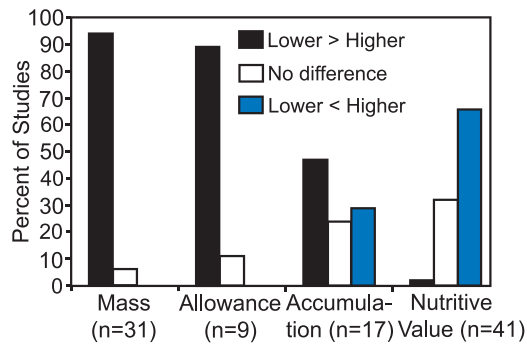
### Forage Quantity

A total of 67 papers contained relevant data, and 48 reported forage mass, forage accumulation, or forage allowance responses to grazing intensity. Treatment variables were primarily stocking rate or sward height.

**Forage Mass.** Forage mass ( $\text{kg ha}^{-1}$ ) is the instantaneous measure of the total dry weight of forage per unit land area above a defined

reference level (e.g., stubble height; Allen et al., 2011). Forage mass was measured in 31 of the 48 studies in which a measure of quantity was taken. In 29 of 31 (94%) studies, forage mass decreased, in most cases linearly, with increasing grazing intensity (Fig. 3.1). For example, forage mass of continuously stocked limpograss (scientific names for species are in Appendix III) pastures in Florida (Newman et al., 2002b), “Coastal” and “Tifton 44” bermudagrass pastures in North Carolina (Burns and Fisher, 2008), and mixed black oat and annual ryegrass pastures in Brazil (Aguinaga et al., 2008) increased linearly with increasing sward height. Pre-graze forage mass of stargrass in rotationally stocked pastures in Jamaica decreased linearly as stocking rate increased (Hernández Garay et al., 2004a). In one of the two studies in which forage mass was unaffected by grazing intensity, the range of stocking rates was low and the pastures were understocked (Valencia et al., 2001).

**Forage Accumulation Rate.** Forage accumulation rate is the increase in forage mass



**FIGURE 3.1.** Percent of studies showing responses to higher and lower grazing intensity for experiments that reported data based on measures of forage mass, forage allowance, forage accumulation, and forage nutritive value. Number of experiments for each data set is indicated in parentheses. “Higher” and “lower” indicate grazing intensity (i.e., higher or lower stocking rate).

per unit area over a specified period of time. This response was measured in 17 of the 48 studies that reported forage quantity responses to grazing intensity. The forage accumulation response was less consistent than forage mass (Fig. 3.1). In nearly half of the studies (47%), forage accumulation was favored by lower grazing intensity, but it was not affected by grazing intensity in four studies (24%) and was increased by increasing grazing intensity in five studies (28%).

Species showing greater forage accumulation in response to increasing grazing intensity typically were ones considered to be grazing tolerant including tall fescue in North Carolina (Burns et al., 2002), perennial ryegrass–white clover in New Zealand (Macdonald et al., 2008), and “Mulato” brachiariagrass in Florida (Inyang et al., 2010). In contrast, forage accumulation decreased with increased grazing intensity for less grazing tolerant warm-season forages, including stargrass in Florida and Jamaica (Mislevy et al., 1989; Alcordo et al., 1991; Hernández Garay et al., 2004a), rhizoma peanut in Florida (Ortega et al., 1992b), and bermudagrass in Florida (Pedreira et al., 1999). Forage accumulation also decreased with increasing grazing intensity for temperate forage mixtures based on orchardgrass, including those with Kentucky bluegrass, quackgrass, red clover, alfalfa, and white clover in Pennsylvania (Carlassare and Karsten, 2002),

and ladino clover in California (Hull et al., 1961, 1965). This response is attributed to the upright growth habit of orchardgrass, which causes it to be relatively intolerant of greater grazing intensity (Carlassare and Karsten, 2002).

Species responses were not always consistent, as black oat–annual ryegrass (Aguinaga et al., 2008), Kentucky bluegrass and white clover (Bryan and Prigge, 1994), stargrass (Adjei et al., 1980), and bermudagrass (Roth et al., 1990) were part of the group for which accumulation did not respond to grazing intensity. Also, in the study with rhizoma peanut, the effect of grazing intensity was more pronounced with short than long rest periods between grazings showing an interaction with grazing frequency (Ortega et al., 1992b). These reports provide clear evidence that the effect of grazing intensity on forage accumulation cannot be predicted in isolation; it depends on forage species, grazing frequency, and the environment.

**Forage Allowance.** Forage allowance is defined as the relationship between forage mass and animal liveweight per unit area at any one time (Sollenberger et al., 2005; Allen et al., 2011). Forage allowance was measured as a response in only nine of 48 studies (Adjei et al., 1980; Conrad et al., 1981; Guerrero et al., 1984; Aiken et al., 1991; Valencia et al., 2001; Fike et al., 2003; Newman et al., 2002b; Hernández Garay et al., 2004a; Inyang et al., 2010) and was a treatment variable in one (Roth et al., 1990). Forage allowance decreased with increasing grazing intensity in eight of nine studies (89%; Fig. 3.1). The single exception occurred when pastures were stocked too lightly to distinguish treatments (Valencia et al., 2001).

Decreasing forage allowance by increasing grazing intensity is expected due to the near universal observation of decreasing forage mass (the numerator in calculation of forage allowance) and increasing number of animal units (the denominator) with increasing grazing intensity. The nature of the response was most often curvilinear (in five of six studies where more than two levels of grazing intensity were investigated, or where the nature of the response was reported) with the rate

of change decreasing with increasing grazing intensity. For example, on stargrass pastures stocked with 200-kg bulls at 2.5, 5.0, and 7.5 head ha<sup>-1</sup> the forage allowance was 7.6, 2.7, and 1.2 kg forage kg<sup>-1</sup> animal liveweight, respectively (Hernández Garay et al., 2004a). This curvilinear relationship is mathematically consistent with linear decreases in forage mass as a function of increasing grazing intensity.

### Forage Nutritive Value

Nutritive value is defined as the chemical composition, digestibility, and nature of digested products of forage (Sollenberger and Cherney, 1995). Forty-one of 67 grazing intensity papers reported nutritive value responses, mainly crude protein (CP), *in vitro* digestion, neutral detergent fiber (NDF), acid detergent fiber (ADF), and lignin. In a few papers, the traditional definition of nutritive value was broadened to include plant part composition and forage bulk density. A limitation of much of the nutritive value literature is that sampling strategies often fail to collect forage that represents the portion of the canopy in which the animals are grazing.

The nutritive value response to increasing grazing intensity was not as consistent as the forage quantity response, yet nearly all studies (40 of 41; 98%) reported either no effect (13 of 41; 32%) or a positive effect (27 of 41; 66%) on nutritive value (Fig. 3.1). Only one (2%) reported a negative effect (Ackerman et al., 2001). In three of the 13 studies showing no effect, the authors cited the relatively narrow range of stocking rates imposed as a reason for lack of response (Valencia et al., 2001; Arthington et al., 2007; Scaglia et al., 2008).

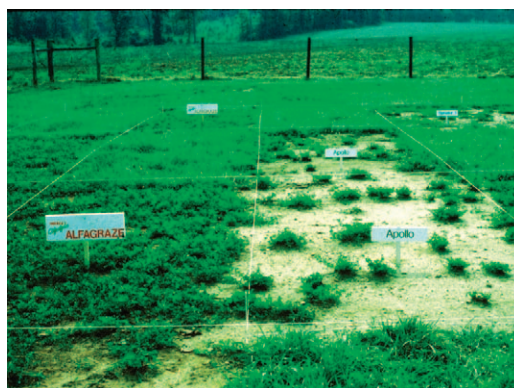
Positive effects of increasing grazing intensity on nutritive value occurred in West Virginia where Kentucky bluegrass–white clover pastures were continuously stocked (Bryan and Prigge, 1994), in an orchardgrass–ladino clover association in California that was rotationally stocked (Hull et al., 1965), with alfalfa in Michigan (Schlegel et al., 2000a), and with a perennial ryegrass–white clover mixture in New Zealand (Macdonald et al., 2008). For C<sub>4</sub> grasses, *in vitro* digestion increased with increasing stocking rate for both Coastal and “Callie” bermudagrass pastures in Texas (Guerrero et al., 1984), for “Tanzania”

guineagrass in Brazil (do Canto et al., 2008), and for digitgrass in tropical Australia (Jones and LeFeuvre, 2006).

The increase in forage nutritive value with greater grazing intensity may seem counterintuitive because there is less forage mass and grazing occurs at lower strata in the canopy. Nutritive value generally decreases from top to bottom of a canopy, particularly for C<sub>4</sub> grasses (Fisher et al., 1991; Holderbaum et al., 1992). However, when canopies are grazed intensively over an extended period of time the leaf proportion of the forage mass is greater and age of regrowth is younger because of shorter intervals between animal visits to individual patches (Roth et al., 1990; Pedreira et al., 1999; Newman et al., 2002a, 2002b; Hernández Garay et al., 2004a; Dubeux et al., 2006).

The positive response of forage nutritive value to increasing grazing intensity may result in limited measureable effects on animal performance because of the associated decrease in forage quantity. For example, digitgrass nutritive value increased with increasing stocking rate in Australia (Jones and Lefeuvre, 2006), but nutritive value was negatively correlated with cattle average daily gain. In the same study, the relationship of forage mass and daily gain was positive (Jones and Lefeuvre, 2006). Other studies have shown that the greater nutritive value associated with higher grazing intensity cannot overcome a quantity limitation (McCartor and Rouquette, 1977; Guerrero et al., 1984; Hernández Garay et al., 2004a).

In a comprehensive review of the grazing literature, forage nutritive value was found to



Grazing tolerant “Alfagraze” (left) and intolerant “Apollo” (right) alfalfa stands following 3 yr of frequent, intense grazing. Photo by Joe Bouton, University of Georgia and Noble Foundation.



Grazed pastures generally have greater species richness than areas that are not grazed. Photo by Carmen Agouridis, University of Kentucky.

1) set the upper limit for average daily gain, 2) determine the slope of the regression of daily gain on stocking rate, and 3) establish the forage mass at which daily gain plateaus (Sollenberger and Vanzant, 2011). In contrast, forage quantity determined the proportion of potential daily gain that was achieved and was the primary driver for direction of the daily gain response (negative) to increasing stocking rate. Thus, choosing which grazing intensity to use must account for the overriding importance of forage mass and forage allowance in affecting animal response.

### Forage Botanical Composition and Species Persistence

Grazing intensity affects pasture productivity and nutritive value and may impact species composition of the sward and persistence of desired species. Twenty-nine of the 67 grazing intensity papers reviewed described botanical composition or persistence-related responses

to grazing intensity. In most cases grazing intensity interacted strongly with other factors, which are explored in this section.

### *Grazing Intensity by Frequency Interaction.*

The importance of grazing intensity by frequency interaction in sward persistence is well established (Sollenberger and Newman, 2007). For example, sainfoin survival was not affected by stubble height when defoliated at seed-shatter stage, but if defoliated more frequently, at bud or flower stage, and grazed to a low stubble height (5 cm), stands were greatly reduced (Mowrey and Matches, 1991).

Weed invasion into rotationally stocked, mixed pastures of the legume Siratro and the grass setaria was greater and legume contribution less when pastures were grazed every 3 wk than every 6 or 9 wk at a range of stocking rates (Jones, 1979). Longer regrowth intervals lessened the impact of high stocking rate on

the legume. In Florida a rhizoma peanut–common bermudagrass mixture (90% peanut at initiation) was stocked rotationally to leave a range of residual forage mass (Ortega et al., 1992a, 1992b). Peanut percentage in the stand after 2 yr was lower with short rest periods, especially when residual forage mass was low, but legume persistence was better with a 42-d rest period. Changes in rhizome mass also reflected the intensity by frequency interaction.

### *Grazing Intensity by Cultivar Interaction.*

Several papers highlight the interaction between cultivar and grazing intensity on persistence. “Alfagraze” and “Apollo” alfalfa were stocked continuously at three levels of forage mass in central Georgia (Bates et al., 1996). After 3 yr of grazing, Alfagraze had 59 plants m<sup>-2</sup> for both the greatest and least forage mass, while less grazing-tolerant Apollo maintained 36 plants at the greatest mass but only 16 plants m<sup>-2</sup> at the lowest forage mass.

In Florida, at high stocking rate, “Bigalta” limpograss was rapidly invaded by common bermudagrass while “Floralta” persisted at both stocking rates (Pitman et al., 1994). Stubble height had varying effects on persistence of three stargrasses in Florida (Mislevy et al., 1989). Weeds contributed less than 10% of forage mass if stubble height was 15 cm or greater for all three cultivars tested, but if stubble height was < 15 cm, weed percentage was 12 to 25% for “Florico” but averaged 6% for “Florona” and “Ona.” These data show that prescribed grazing intensity is a function of forage species and also dependent to a large degree on the cultivar.

*Multispecies Pastures.* When multiple forage species are present, the complexity of selecting the optimal grazing intensity increases, particularly when growth characteristics of the species vary widely. For example, when limpograss-dominated grass pastures in Florida were stocked continuously to a range of canopy heights, the bunchgrass weed vaseygrass was essentially removed by grazing to 20 cm (Newman et al., 2003). In contrast, percentage of the stoloniferous weed common bermudagrass increased markedly with the 20-cm height, but remained low when a 40-cm height was maintained.

In grass-legume pastures, legumes often are considered to be less persistent under high stocking rates than grasses; however, the species present in the sward has a major effect on the response. Mixtures of the stoloniferous creeping signalgrass, with either ovalifolium or tropical kudzu, were continuously stocked with 2 or 3 steers ha<sup>-1</sup> (Cantarutti et al., 2002). Average legume percentage was 30 and 10 for the low and high stocking rates, respectively. Higher stocking rate favored the aggressive, relatively decumbent grass.

The opposite was observed when a palisadegrass–pinto peanut pasture in Costa Rica was stocked continuously at 600 and 1200 kg liveweight ha<sup>-1</sup> (Hernandez et al., 1995). During 3 yr of grazing, pinto peanut contributed 34% of dry matter on offer at the high but only 6% at the low stocking rate. This was due to its prostrate, stoloniferous growth habit that conveyed greater tolerance of high stocking rates than the upright-growing palisadegrass.

In California the percentage of white clover increased as stocking rate increased reflecting greater tolerance of close grazing than orchardgrass. Similarly, the greatest percentage of white clover in a mixed pasture in Ireland occurred at the highest stocking rate (Conway, 1968). In Pennsylvania, when a complex mixture was stocked rotationally for 2 yr with grazing initiation/termination at heights of 20/5 cm or 27/7 cm, forage accumulation of red clover, alfalfa, and orchardgrass was greater for tall than short pastures whereas Kentucky bluegrass accumulation was greater for short than tall (Carlassare and Karsten, 2002). This can be attributed, in part, to tillering response to stocking rate; greater stocking rate decreased tiller density for upright-growing orchardgrass and increased tiller density for prostrate-growing Kentucky bluegrass (Fales et al., 1995).

*Plant Adaptations to Grazing Intensity.* Each plant within a population has some ability to adapt to stress by changing its morphology, an attribute termed phenotypic plasticity (Nelson, 2000). Phenotypic plasticity is reversible and includes changes in size, structure, and spatial positioning of organs (Huber et al., 1999) such that optimization of canopy leaf area at lower defoliation height may be achieved through



When multiple forage species are present, the complexity of selecting the optimal grazing intensity increases”



...conservation planning activities should prioritize prescription of the appropriate stocking rate or sward height.”

a decrease in mean tiller size and an increase in tiller density (Matthew et al., 2000). For example, tiller density of caucasian bluestem was more than double at a high than a low grazing intensity while tiller mass was 10 times greater for low than for high grazing intensity (Christiansen and Svejcar, 1988). Phenotypic plasticity has limits, and if defoliation is too severe, the leaf area, substrate supply, and tiller production decrease, which in turn reduces tiller survival and weakens the stand (Matthew et al., 2000).

Phenotypic plasticity varies among species (Gibson et al., 1992) and can be related to grazing tolerance. When two *C<sub>4</sub>* bunchgrasses were defoliated frequently and severely, buffelgrass produced more horizontal tillers and achieved a 10-fold greater leaf area below defoliation height than did red oatgrass, which retained its upright tillering orientation (Hodgkinson et al., 1989). Thus, phenotypic plasticity of buffelgrass contributed to its greater grazing tolerance than red oatgrass.

Below-ground responses also impact plant persistence. Root length and root mass of caucasian bluestem pastures were about 30% less after 1 yr and 45% less after 2 yr for high versus low grazing intensity (Christiansen and Svejcar, 1988). Root-rhizome mass of rhizoma peanut was 80% less and ground cover was 38% less after 4 yr of defoliation to 2.5 cm compared with 10 cm (Mislevy et al., 2007). Root mass of stargrass was reduced 3 to 10 times by stubble height of 5 cm vs. 15 cm, and stem base carbohydrate reserves were reduced by 15 to 22 g kg<sup>-1</sup> (Alcordero et al., 1991). In Texas root carbohydrate reserves of sanfoin were lower following high vs. medium or low grazing intensity (Mowrey and Matches, 1991).

**Species Richness Response to Grazing Intensity.** There is limited information in the U.S. literature on this subject. In Israel species richness of annual legumes was lowest in non-grazed sites and increased gradually with increasing grazing intensity; however, extremely high grazing intensity reduced mean legume richness (Noy-Meir and Kaplan, 2002). The 24 species with a positive response to grazing intensity had low, decumbent, or prostrate growth habits. Intermediate response species were more upright types, but the most negative

effect of grazing intensity was associated with twining species. Greater species richness of grazed vs. non-grazed pastureland was also reported in several studies in Iowa (Barker et al., 2002; Guretzky et al., 2004, 2005, 2007).

### Summary and Recommendations: Grazing Intensity

Review of the grazing intensity literature affirms its often-stated characterization as the most important grazing management decision for pastureland. Because of the major effect of grazing intensity on productivity, nutritive value, botanical composition, and persistence of pasturelands, conservation planning activities should prioritize prescription of the appropriate stocking rate or sward height. If conservation planning fails to identify, achieve, and maintain the proper grazing intensity, then choice of stocking method, season of grazing and deferment, or any other grazing strategy will not be able to overcome this failure.

Several shortcomings were identified in the grazing intensity literature. A major shortcoming is inconsistency in forage terminology. Pastureland scientists and advisers should adopt a standard terminology, preferably based on that already developed by the Forage and Grazing Terminology Committee (Allen et al., 2011). Forage mass, forage accumulation, and forage allowance are preferred terms. Others such as yield and forage available are vague, confusing, and ill-advised for reporting quantity measures on pastureland. The term *forage quality* is widely misused and should be reserved for measures of animal performance or intake. The term *nutritive value* is correctly used when chemical composition and digestibility of the plant tissue have been quantified.

A recurring methodological weakness in the nutritive value literature is that sampling procedures may not effectively represent the portion of the sward canopy the animals are grazing. Thus, estimates of diet nutritive value may be flawed, and in some cases the comparisons among treatments biased.

Most literature reports on botanical composition and persistence are 2-yr studies, which for many species and environments is insufficient to develop or even predict the

long-term balance of species composition and expression of phenotypic plasticity in response to the grazing management. Although short grant funding cycles, limited length of graduate student research projects, and high costs of grazing research are contributors, they cannot be excuses. Short-term studies contribute to inadequate and often misleading knowledge that may not represent long-term botanical composition and persistence responses.

### STOCKING METHOD

Stocking method is “a defined procedure or technique to manipulate animals in space and time to achieve a specific objective” (Allen et al., 2011). It is important to distinguish *stocking method* from *grazing system* because they are often used interchangeably despite having different meanings. Grazing system is “a defined, integrated combination of soil, plant, animal, social and economic features, stocking method(s) and management objectives designed to achieve specific results or goals” (Allen et al., 2011). As defined, stocking method is but one component of the overarching grazing system.

For this assessment, stocking method refers to the manner in which animals are stocked or have access to pastures and paddocks (pasture subdivisions, if present) during the grazing season. Choice of *stocking method* is separate from *grazing intensity*; a particular stocking method may include a wide range of grazing intensities that are based on stocking rates or forage height or mass. Many stocking methods have been described (Vallentine, 2001; Allen et al., 2011), but each is derived from continuous or some form of rotational stocking. Under continuous stocking, animals have unlimited and uninterrupted access to the grazing area throughout the period when grazing is allowed (Allen et al., 2011). Rotational stocking utilizes recurring periods of grazing and rest among paddocks in a grazing management unit. Often the objective of rotational stocking is to achieve efficient and more uniform defoliation of the pasture and to optimize pasture productivity and persistence.

Plant-related advantages of rotational over continuous stocking purportedly include increased pasture carrying capacity, improved plant persistence (Matches and Burns, 1995), and more uniform use of an

extensive pasture area (Hart et al., 1993). Whether these advantages are supported by the scientific literature has been a topic of much debate and has generated considerable disagreement among scientists and graziers. For example, Bransby (1991) stated “few topics in agriculture have been addressed with such charismatic language and such abandonment of scientific evidence and logic” as have discussions regarding rotational and continuous stocking.

Data from 57 papers were used to determine the effect of stocking method on measures of forage quantity, nutritive value, botanical composition, and persistence. Achieving meaningful comparisons of plant responses under continuous and rotational stocking is complex. Sampling methods used to quantify these responses vary widely in the literature, and in some cases the sampling method may provide biased comparisons of stocking methods.

### Forage Quantity

Many reports suggest rotational stocking allows greater average stocking rates (i.e., carrying capacity) than continuous stocking (Blaser et al., 1986), inferring that rotationally stocked pastures have greater forage accumulation rate and/or more efficient utilization of existing forage mass than continuously stocked pastures. Unfortunately, few stocking method studies have measured



Whether these advantages are supported by the scientific literature has been a topic of much debate”

Cattle use their tongue to select and gather leaf of the woody legume leucaena before biting. Photo by Lynn Sollenberger, University of Florida.





Greater average stocking rate for rotationally vs. continuously stocked pastures was reported on bermudagrass (and several other species).”

these independent responses, so in most cases indirect measures of pasture productivity, e.g., average stocking rate or animal days of grazing, are the only quantity-related responses available for making comparisons among methods.

There were 27 papers reviewed that included both rotational and continuous stocking treatments and reported responses related to quantity of forage. Of these, 23 (85%) reported an advantage in forage quantity response for rotationally vs. continuously stocked pastures. From the 23 studies cited that showed greater forage quantity-related responses on rotationally than continuously stocked pastures, 16 were described sufficiently that the magnitude of the difference could be determined (Table 3.2). For these, the advantage for rotational stocking ranged from 9% to 68%, with an average of 30%.

#### *Indirect Measures of Forage Quantity.*

Average stocking rate is the most common indirect measure of forage quantity. Greater average stocking rate for rotationally vs. continuously stocked pastures was reported on bermudagrass in Florida (Mathews et al., 1994b), wheat–annual ryegrass in Arkansas (Aiken, 1998), alfalfa–grass mixtures in Illinois (Bertelsen et al., 1993), orchardgrass–legume mixtures in Virginia (Bryant et al., 1961), “Plains” old world bluestem in Oklahoma (Volesky et al., 1994), switchgrass and big bluestem in Iowa (George et al., 1996), orchardgrass–perennial ryegrass–tall fescue–white clover mixtures in California (Hull et al., 1967), and bermudagrass in Arkansas (Tharel, 1989). Plains old world bluestem pastures in Oklahoma had a 34% higher stocking rate using frontal stocking (cattle move a sliding fence to access new forage, a back fence restricts regrowth) than for continuous stocking (Volesky, 1994). He suggested frontal stocking increases tillering, keeps the canopy near optimum leaf area index (LAI), provides a greater proportion of young tissue, and removes more old tissue.

*Forage Mass, Accumulation Rate, and Canopy Photosynthesis.* Greater forage mass was reported on rotationally than on continuously stocked bermudagrass–tall fescue

pastures in Georgia (Hoveland et al., 1997). In Florida average forage accumulation rate of “Pensacola” bahiagrass over three growing seasons was greater for rotationally than continuously stocked pastures (Stewart et al., 2005). With phalaris–subterranean clover mixtures in Australia, rotational stocking supported greater forage accumulation and stocking rates of ewes than did continuous stocking (Chapman et al., 2003).

Canopy photosynthesis of perennial ryegrass in the United Kingdom was greater in continuously stocked swards (LAI = 1) immediately following defoliation of the rotationally stocked treatment (to LAI of 0.5), but this soon reversed because percentage of young leaves increased more rapidly in rotational swards (Parsons et al., 1988). These authors found that long-term rates of canopy photosynthesis of rotationally stocked perennial ryegrass pastures exceeded those of continuously stocked pastures even when defoliation was severe and regrowth periods were relatively short.

#### *Efficiency of Utilization of Forage Mass.*

Greater forage quantity-related responses in rotationally than continuously stocked pastures may be due to greater efficiency of utilization of forage mass. Norton (2003) hypothesized that livestock are more evenly distributed and encounter more forage in smaller paddocks or at higher stocking densities, like those used with rotational stocking. This was supported by a Utah study of mixed-grass pastures using the same stocking rate, but different paddock sizes (Barnes et al., 2008). In most cases, paddocks  $\leq 4$  ha were grazed more evenly than larger paddocks and had a lower proportion of nonutilized area. Similarly, Heitschmidt (1988) concluded, “Because intensively managed rotational type grazing systems facilitate livestock distribution by increasing livestock density, spatial variation in grazing pressure index is reduced. This in turn improves the efficiency of harvest of all forage that is available within a given unit or pasture.”

Rotational stocking generally increases utilization by 5% to 15% over continuous stocking on small pastures in research

**TABLE 3.2.** Proportional advantage of rotational (R) vs. continuous (C) stocking for quantity-related responses.

Reference	Species	Location	Treatments	Response compared	Advantage of rotational vs. continuous
Aiken, 1998	Wheat-ryegrass	Booneville, AR	C vs. 3 and 11-paddock R	Average stocking rate	34% (2190 [R] vs. 1640 [C] kg liveweight ha <sup>-1</sup> )
Bertelsen et al., 1993	Alfalfa	Baylis, IL	C vs. 6 and 11-paddock R	Average stocking rate	42%; (4.31 [R] vs. 3.03 [C] heifers ha <sup>-1</sup> )
Bryant et al., 1961	Temperate grass-legume mixtures	Blacksburg, VA	C vs. 10-paddock R	Average stocking rate	30, 19, and 22% (avg. of 24%) for 3 mixtures
Chapman et al., 2003	Phalaris-sub clover	Victoria, Australia	C vs. 4-paddock R	Average stocking rate	9%; supported higher SR (14.9 vs. 13.7 ewes ha <sup>-1</sup> )
Davis and Pratt, 1956	Alfalfa-white clover-bromegrass	Wooster, OH	C vs. 6-paddock R	Total digestible nutrients ha <sup>-1</sup>	42% (3240 vs. 2280 kg TDN ha <sup>-1</sup> )
Hoveland et al., 1997	Common bermudagrass-tall fescue	Eatonton, GA	C vs. 12-paddock R	Hay fed and avg. stocking rate	31% less hay and 38% greater stocking rate
Hull et al., 1967	Temperate grass-legume mixture	Davis, CA	C vs. 6-paddock R	Seasonal carrying capacity	17% on average across treatments (1137 vs. 967 animal days ha <sup>-1</sup> )
Mathews et al., 1994b	Bermudagrass	Gainesville, FL	C vs. 15-paddock R	Seasonal carrying capacity	16%; average SR of R was 3525 vs. 3035 kg liveweight ha <sup>-1</sup> d <sup>-1</sup> for C in 2 yr
Popp et al., 1997b	Alfalfa-meadow bromegrass	Manitoba, CN	C vs. 10-paddock R	Seasonal carrying capacity (steer days ha <sup>-1</sup> )	10%; 213 vs 193 steer days ha <sup>-1</sup> (4-yr avg.)
Stewart et al., 2005	Bahiagrass	Gainesville, FL	C vs. 4 different R treatments	Herbage accumulation rate	68%; 69 vs. 41 kg ha <sup>-1</sup> d <sup>-1</sup>
Tharel, 1989	Bermudagrass	Arkansas	C vs. R	Seasonal carrying capacity	34%; grazing days was 1150 ha <sup>-1</sup> for R vs. 860 for C
Volesky, 1994	Old world bluestem	El Reno, OK	C vs. frontal R	Seasonal carrying capacity (stocking rate)	34%
Volesky et al., 1994	Old world bluestem	El Reno, OK	C vs. 2-paddock R and frontal R	Seasonal carrying capacity (steer days)	24%; 540 for frontal vs. 436 steer days ha <sup>-1</sup> for C
Overall					Range 9–68%; average 30%

studies, but improved utilization from use of rotational stocking may be greater in 50- to 100-ha pastures that are common on farms (Saul and Chapman, 2002). Teague and Dowhower (2003), from a Texas rangeland perspective, state that patch-selective grazing means that the effective stocking rate is much greater than intended on heavily used patches, resulting in deterioration in these patches. They suggest that the effect may be more pronounced on larger, heterogeneous areas but indicate that most research has been conducted on small, homogeneous experimental units.

The concepts of potentially greater forage accumulation and improved utilization of forage mass under rotational stocking were integrated by Saul and Chapman (2002), who suggested the greater homogeneity of utilization of rotationally stocked pastures is partially responsible for greater forage accumulation. They reasoned that amount of post-grazing residual mass and length of regrowth interval are affected by both stocking methods. In continuous stocking, they are affected at the individual bite scale and are largely under the control of the animal, but in rotational they are affected at the paddock scale and are under



Rotational stocking generally allows manager control over postgrazing residual and, particularly, regrowth interval”

the control of the manager. Rotational stocking generally allows manager control over post-grazing residual and, particularly, regrowth interval, whereas continuous stocking does not, beyond what can be achieved through adjusting stocking rate.

An extreme example is the patch-grazing phenomenon commonly seen in continuously stocked pastures. The post-grazing residual is too short and regrowth interval inadequate in the heavily grazed patches. Rotational stocking allows better control over at least one of the critical variables, the length of the regrowth period. Even if the pasture is grazed below the optimum height or mass, it can be allowed time to recover and move into what the authors term Phase II of plant growth (Fig. 3.2). This difference leads to the conclusion that, especially at high stocking rates or during times of feed deficit, rotational stocking should lead to better control of average leaf area, faster growth rates, and greater forage accumulation.

**Number of Paddocks per Pasture.** Eleven papers reviewed studied the effect of length of stocking period within one cycle of rotational stocking (i.e., a function of number of paddocks) on forage accumulation or average stocking rate. The literature is not consistent, as five of 11 papers reported advantages in forage quantity by increasing number of paddocks and decreasing the duration of the grazing period,

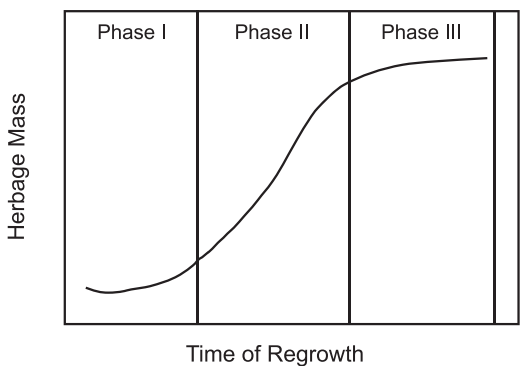
five reported no effect, and one reported a disadvantage of greater paddock number. Four of the five studies reporting no effect used a fixed stocking rate, with forage mass the measure of production. There was no common thread in forage species among studies as they included alfalfa (Schlegel et al., 2000b), cool-season forage mixtures (Bertelsen et al., 1993; Phillip et al., 2001), bahiagrass (Stewart et al., 2005), and bermudagrass (Aiken, 1998).

Studies showing a quantity advantage for rotational stocking with a greater versus a smaller number of paddocks used a variable stocking rate approach and equalized post-graze forage mass or stubble height. The average advantage in stocking rate or animal days of grazing ha<sup>-1</sup> was 28% for pastures with a greater number of paddocks and represented a wide range of forage species including orchardgrass (33% advantage; Holmes et al., 1952), bermudagrass (18%; Mathews et al., 1994b), a complex cool-season mixture (26%; Kuusela and Khalili, 2002), and old world bluestem (34%; Volesky, 1994; Volesky et al., 1994). The small number of studies from which the average advantage was derived suggests that conclusions should be drawn cautiously until additional research has been conducted.

### Forage Nutritive Value

Forage nutritive value may be greater on continuously than rotationally stocked pastures if forage quantity is not limiting at that stocking rate (Sollenberger and Newman, 2007). The increase is associated with greater opportunity for selection and the tendency of animals to make frequent visits to the same grazing stations, resulting in consumption of less mature forage (Valentine, 2001).

The literature comparing forage nutritive value responses of continuously and rotationally stocked pastures is difficult to interpret, in part because of inadequate experimental methodology. Many reports fail to account for the large differences in nutritive value that occur during the course of a grazing period in rotationally stocked pastures. Samples from continuously stocked pastures have been compared with those from rotationally stocked pastures taken at a single point in time, most often at the beginning of a grazing period.



**FIGURE 3.2.** Accumulation of forage mass during a regrowth period follows a sigmoid curve as the canopy develops from low mass (Phase 1: low accumulation rate) to intermediate mass (Phase 2: high accumulation rate) to high mass (Phase 3: little or no net accumulation due to balance between new growth and senescence). Adapted from Saul and Chapman (2002).

**TABLE 3.3.** Chemical composition of forage and extrusa from rotationally (6 and 11 paddocks per pasture) and continuously stocked pastures. Rotationally stocked pastures were sampled pre- and post-graze, and extrusa was collected at the beginning and end of grazing periods. Continuously stocked pastures were sampled on the same dates as rotational treatments. Data are adapted from Bertelsen et al. (1993).<sup>1</sup>

Chemical constituent	Stocking method	Pasture samples		Extrusa samples	
		Pre-graze	Post-graze	Beginning	End
		g kg <sup>-1</sup>			
NDF	Continuous	680 a	692 a	584 a	571 b
	6-paddock	577 b	668 a	453 b	641 a
	11-paddock	581 b	687 a	380 c	656 a
	SE	16	10	19	19
ADF	Continuous	427 a	437 a	348 a	330 b
	6-paddock	358 b	427 a	282 b	402 a
	11-paddock	366 b	426 a	259 b	409 a
	SE	12	6	9	9
ADL	Continuous	72.6 a	77.2 a	57.5 a	53.2 b
	6-paddock	61.3 b	79.3 a	44.7 b	77.1 a
	11-paddock	61.3 b	78.1 a	42.5 b	71.2 a
	SE	2.6	3.4	3.1	3.1
CP	Continuous	122 b	110 a	187 b	183 a
	6-paddock	152 a	117 a	219 a	140 b
	11-paddock	166 a	121 a	238 a	128 b
	SE	8.0	4.0	8.0	8.0

<sup>1</sup>Means within a chemical constituent and column are not different if followed by the same letter. SE indicates standard error.

In addition, sampling strategies used on continuously stocked pastures often result in collection of forage that does not represent the portion of the canopy from which the animal is selecting.

Data from Bertelsen et al. (1993) showed how sampling approach can affect the conclusions drawn. In their Illinois study, an alfalfa (50%)–tall fescue (40%)–orchardgrass (10%) mixture was stocked continuously or rotationally, the latter including 6- and 11-paddock treatments. All treatments were grazed using a variable stocking rate to maintain a stubble height (post-graze for rotational) of 8 cm to 15 cm. Pasture samples to measure nutritive value were clipped to a 5-cm height pre-graze and post-graze on rotational treatments, and continuous pastures were sampled at comparable times in the same manner. In addition, extrusa samples were taken by reticulorumen evacuation at times similar to those of the pasture samples, and apparent total tract digestion was measured.

If pre-graze pasture samples or extrusa samples taken at the beginning of the stocking period were used to compare treatments, the nutritive value for the two rotational treatments generally was not different, but both were lower in NDF, ADF, and lignin, and higher in CP than the continuous treatment (Table 3.3). Based on post-graze pasture samples, there was no difference among treatments, but based on end-of-stocking-period extrusa samples, continuous had greater nutritive value than rotational (Table 3.3). Total tract digestibility of OM, NDF, ADF, and CP were not different among treatments. Thus, depending on the type of sample chosen for comparison, all possible conclusions can be drawn from the same study, i.e., that continuous is greater than rotational, that rotational is greater than continuous, or that there is no difference.

#### *Rotational vs. Continuous Stocking.*

Fourteen papers were reviewed that compared nutritive value of continuously and rotationally stocked pastures, but only four papers reported



Purported advantages of rotational vs. continuous stocking include superior persistence of grazing-sensitive forage species.”

sampling of the grazed portion of the canopy (by hand-plucking or use of fistulated cattle; especially relevant for continuous stocking) and sampled in such a way as to address the changes that occur during the stocking period on a paddock of a rotationally stocked pasture. No difference in nutritive value was found between rotational and continuous stocking of an alfalfa–tall fescue–orchardgrass mixture in Illinois (Bertelsen et al., 1993), bermudagrass in Florida (Mathews et al., 1994b), bahiagrass in Florida (Stewart et al., 2005), and crested wheatgrass in Utah (Olson and Malechek, 1988).

Of the other 10 papers where concerns about sampling method exist, six found no difference between stocking methods, three reported that rotational resulted in greater forage nutritive value than continuous, and one indicated that there were interactions of season with method of grazing. Thus, the effect of continuous vs. rotational stocking methods on forage nutritive value remains inconclusive. Given the issues related to pasture sampling, at present we must defer to measures of animal performance to assess this response to stocking method. This information is summarized later in the chapter.

**Number of Paddocks per Pasture.** Of the eight relevant studies, six (75%) found no difference in forage nutritive value due to number of paddocks, i.e., length of stocking periods. These included an alfalfa–tall fescue–orchardgrass mixture (6 vs. 11 paddocks; Bertelsen et al., 1993), bermudagrass (3 vs. 15 paddocks; Mathews et al., 1994b), bermudagrass (3 vs. 11 paddocks; Aiken, 1998), alfalfa (4 vs. 13 paddocks; Schlegel et al., 2000a), cool-season grasses (6 vs. 16 paddocks; Phillip et al., 2001), and bahiagrass (2, 4, 8, and 22 paddocks; Stewart et al., 2005). Two studies found differences due to number of paddocks, but one favored more paddocks (Kuusela and Khalili, 2002) and one favored fewer paddocks (Aiken, 1998).

### Forage Botanical Composition and Species Persistence

Purported advantages of rotational vs. continuous stocking include superior persistence of grazing-sensitive forage species (Van Keuren and Matches, 1988). For example, after 3 yr of grazing alfalfa–white

clover–smooth brome grass in Ohio, excellent alfalfa stands remained on rotationally stocked pastures, but on continuously stocked pastures brome grass increased and alfalfa decreased (Davis and Pratt, 1956). There were 15 papers that addressed this issue, but the body of literature suggests that although stocking method plays a role in botanical composition and plant persistence, numerous factors contribute to the responses. Interacting factors include grazing intensity, morphology/growth habit of the grazed forage, cultivars within forage species, and the opportunity for diet selection.

**Grazing Intensity and Stocking Method Interactions.** Pastures of rhizoma peanut in Florida grazed for 2 yr to a post-graze residual forage mass of 500 kg ha<sup>-1</sup> had less than 25% peanut in forage mass when grazing frequency was 7 d (simulated continuous stocking) and 55% when grazed every 49 d (rotational). If post-graze residual forage mass was 1500 kg ha<sup>-1</sup>, stocking method had less effect; percentage peanut was 70% and 85% for simulated continuous and rotational treatments, respectively. Alfalfa–meadow brome grass pastures were continuously stocked in Manitoba, Canada (Popp et al., 1997a). Alfalfa percentage was greater for high than low stocking rates during 4 yr because high stocking rates had a negative impact on the grass. In contrast, when pastures were rotationally stocked, there was no consistent effect of stocking rate on alfalfa percentage.

**Plant Morphology and Stocking Method Interactions.** In Virginia legume percentage by weight was higher with rotational vs. continuous stocking for alfalfa–orchardgrass and white clover–orchardgrass mixtures, but the increase was much greater for alfalfa than for white clover (Bryant et al., 1961). The stoloniferous white clover was likely more tolerant of continuous stocking, and it may have been at a competitive disadvantage for light during a greater portion of the season under rotational stocking. Legumes are not always favored by rotational stocking. In a phalaris–subclover mixture in temperate Australia, rotational stocking favored forage accumulation of the taller-growing grass, but reduced yields of the low-growing legume compared with continuous stocking (Chapman

et al., 2003). Subclover was favored by continuous stocking in part because of a better light environment for seedling recruitment. Callie bermudagrass pastures in Florida were stocked continuously and rotationally, and after 2 yr the stand averaged 85% Callie for both rotational treatments compared with 62% for continuous stocking (Mathews et al., 1994b). Continuous stocking provided a more favorable light environment than rotational allowing low-growing, less desirable common bermudagrass and bahiagrass to persist.

#### *Cultivar by Stocking Method Interactions.*

In Florida, when stocked continuously for 3 yr, upright-growing “Arbrook” rhizoma peanut decreased in percentage of forage mass from 89% to 66% compared with a decrease from 90% only to 87% for lower-growing “Florigraze” (Hernández Garay et al., 2004b). Common bermudagrass was overseeded with endophyte-free (Hoveland et al., 1997) or with endophyte-infected tall fescue in Georgia (Kuykendall et al., 1999b). After 3 yr of grazing, common bermudagrass had 14% more basal cover for continuous than rotational stocking when associated with endophyte-free fescue. In contrast, when associated with endophyte-infected tall fescue, common bermudagrass had 7% less basal cover under continuous than rotational stocking. This interaction was attributed to grazing preference for bermudagrass over infected tall fescue.

Pasture- and hay-type alfalfa cultivars were stocked rotationally or continuously in pure stands and in mixtures with meadow bromegrass in Manitoba, Canada (Katepa-Mupondwa et al., 2002). The four pasture types were more persistent than cultivars developed for hay use due to high mortality of the hay types under continuous stocking. After 3 yr of grazing in Georgia, populations of alfalfa ranged from 4 to 57 plants  $\text{m}^{-2}$ , demonstrating large genetic differences in persistence under heavy continuous stocking (Smith et al., 1992). In another Georgia study, after 3 yr of continuous stocking, hay types of alfalfa had 6 to 9 plants  $\text{m}^{-2}$ , grazing types had 40 to 48 plants  $\text{m}^{-2}$ , and a type selected for tolerance to continuous stocking had 64 plants  $\text{m}^{-2}$  and produced the most regrowth of any cultivar (Smith et al., 1989).

*Diet Selection.* The degree to which stocking method affects opportunity for diet selection can influence pasture botanical composition responses. When cattle selected bermudagrass over endophyte-infected tall fescue, it lead to greater bermudagrass decline under continuous than rotational stocking (Kuykendall et al., 1999b). When Plains old-world bluestem was grazed using frontal rotational or continuous stocking in Oklahoma, a greater proportion of grass and lower proportion of forbs was seen on rotationally stocked pastures. The very high stocking rates associated with frontal stocking apparently reduced opportunity for selection; i.e., forbs were avoided under continuous stocking but grazed using frontal stocking.

*Number of Paddocks per Pasture.* Only two studies were found that evaluated the effect of numbers of paddocks in rotationally stocked pastures on botanical composition. Botanical composition was not affected by number of paddocks when alfalfa was grazed at two stocking rates in rotational pastures with either 4 or 13 paddocks in Michigan (Schlegel et al., 2000b). In Finland, content of white plus alsike clover was 17% and 13%, respectively, in pastures with 20 and 6 paddocks (Kuusela and Khalili, 2002).

#### *Species Richness and Stocking Method.*

Relatively few studies have assessed rotational and continuous stocking effects on species richness, i.e., the number of species within a biological community. In Iowa, after bromegrass and reed canarygrass pastures were overseeded with 11 temperate legumes, the continuously stocked swards had greater species richness at a small scale than rotationally stocked swards (Guretzky et al., 2007). At a larger scale, continuous stocking had greater species richness than rotational only for bunch grasses. In Wisconsin both rotational and continuous stocking supported high species richness and proportions of native plants, but rotational provided better erosion control and aquatic habitat protection (Paine and Ribic, 2002). Several studies from the Czech Republic and Iowa have found greater species richness in grazed vs. non-grazed areas (Pykälä, 2003; Guretzky et al., 2007; Pavlu et al., 2007). In contrast, Tracy and Sanderson (2000) found little effect from land use, including grazing, on plant species richness in the northeastern USA.



After 3 yr of grazing in Georgia, populations of alfalfa... demonstrat(ed) large genetic differences in persistence under heavy continuous stocking.”

The weanling bulls in the foreground were stocked at 7.5 head ha<sup>-1</sup> on stargrass pastures for a 300-d grazing season in Jamaica while the bull in the background was part of a group stocked at 2.5 head ha<sup>-1</sup>. Average daily gain was 0.31 and 0.68 kg for animals from high and low stocking rate treatments, respectively (Hernández Garay et al., 2004). Photo by Lynn Sollenberger, University of Florida.

### Summary and Recommendations: Stocking Method

There is sufficient evidence from the pastureland literature (23 of 27 studies) to conclude that rotational stocking increases forage quantity-related responses relative to continuous stocking, and the average advantage for rotational stocking is about 30%. For this advantage to occur, rotationally stocked pastures must have either greater herbage accumulation rate or greater use efficiency of the forage mass. There are rational arguments to support both, but few studies have directly measured these responses. In most cases the quantity-related advantages of rotational stocking were measured in terms of forage mass, average stocking rate, or number of animal days of grazing, etc.

The effect of stocking method on forage nutritive value is inconclusive based on the

current literature due largely to limitations in sampling methods. The literature supports a conclusion that stocking method can alter pasture botanical composition and persistence, but in many situations, interactions with other factors make it impossible to generalize about the direction and magnitude of the responses. Likewise, with rotational stocking, the literature is inconclusive as to whether the number of paddocks per pasture affects plant productivity, nutritive value, and plant persistence. The literature supports the conclusion that grazed grasslands maintain greater species richness than non-grazed areas indicating that prescribed grazing is a key component of efforts to sustain species diversity of grassland communities.

In total, the literature supports the thesis that stocking method is an important grazing



management decision. It is evident, however, that stocking method cannot compensate for inappropriate grazing intensity (stocking rate or sward height). Thus, it is imperative that grazing intensity receive primary focus in development of grazing recommendations, with stocking method used to fine tune the prescribed grazing practice.

### SEASON OF GRAZING AND DEFERMENT

Timing grazing events is a prescribed grazing strategy that is thought to affect species composition and vigor of grassland communities. Timing is usually defined based on season of the year, and the associated environmental conditions, or plant growth stage. Objectives of controlling season of grazing may include 1) optimizing year-round distribution of forage quantity and nutritive value, 2) sustaining sward cover and improving persistence, and 3) facilitating seed production and natural reseeding. To assess the benefits of timing of grazing, the review was organized around the following general topical categories: 1) stockpiling for out-of-season use; 2) timing of grazing within the growing season in terms of initiation, termination, or deferment of grazing; and 3) timing of grazing for seed production and seedling recruitment. Fifty-two papers provided the basis for this assessment.

#### Stockpiling for Out-of-Season Use

Stockpiling, one of the most-used approaches of deferment of grazing, allows forage to accumulate in the absence of defoliation for use at a later time when growth of pasture is limited. There is abundant literature on this practice. Of the 52 papers reviewed for this section, 27 addressed stockpiling specifically and 15 of the 27 studied tall fescue. Common research topics were effects of forage species, nitrogen (N) fertilization rates, and timing of initiation and termination dates of stockpiling on forage nutritive value, distribution of quantity, plant growth in subsequent growing seasons, and toxicosis associated with endophyte-infected tall fescue.

**Forage Quantity.** In Virginia stockpiling tall fescue during autumn provided forage for winter that extended the grazing season and minimized hay feeding compared with other forage systems (Allen et al., 1992b). Allocating

0.27 ha of stockpiled tall fescue per stocker animal provided grazing from November through March with supplemental hay required only for 33 d (Allen et al., 1992a).

Date of initiation of stockpiling varies widely depending on the forage species and environment. In the upper Midwest USA, early initiation is often needed. For smooth brome grass in Minnesota, initiating stockpiling about 1 July, after seedhead production ended, optimized forage and leaf mass in October (Cuomo et al., 2005). In Nebraska delaying initiation of stockpiling of eight cool-season grasses from 15 July to 15 August reduced herbage mass in November by 30% (Volesky et al., 2008). Due to the longer growing season, later initiation is common in warmer regions of the USA and in other countries. Yet late initiation of stockpiling reduced quantity of forage for winter grazing in West Virginia with tall fescue (Collins and Balasko, 1981a), in West Virginia with a white clover–orchardgrass mixture (Belesky and Fedders, 1995), and in Ireland with perennial ryegrass or ryegrass–white clover pastures (Hennessy et al., 2006). Initiating stockpiling of bermudagrass in Arkansas in September produced only 30% to 40% as much as that initiated in August (Scarborough et al., 2004), but success depended upon August rainfall.

Extending the duration of stockpiling of eight cool-season grasses from November to February in Nebraska decreased herbage mass by 18% to 24% due to winter weathering losses (Volesky et al., 2008). Stockpiled forage mass of seven grasses in Wisconsin decreased 22% to 55% from first frost to March, depending on location and length of snow cover (Riesterer et al., 2000). Timothy and late-maturing orchardgrass needed to be grazed by December in that environment, while tall fescue, early-maturing orchardgrass, and reed canarygrass could be used throughout the December through March period.

Comparing different latitudes, forage accumulation of five cool-season grasses and white clover in Prince Edwards Island, Canada, was negligible after 56 d of stockpiling (Kunelius and Narasimhalu, 1993), while in Missouri tall fescue achieved maximum dry matter (DM) accumulation in mid-



It is evident, however, that stocking method cannot compensate for inappropriate grazing intensity (stocking rate or sward height).”



the increase in yield with duration of stockpiling must be balanced with the decrease in nutritive value.”

November after initiation of stockpiling on 1 August (Gerrish et al., 1994). Forage mass changed little after October for bahiagrass, bermudagrass, and kikuyugrass following August initiation of stockpiling in Texas (Evers et al., 2004). In Florida, late-summer stockpiled limpograss yield increased through 1 November and decreased through the winter and spring (Quesenberry and Ocumpaugh, 1982).

**Forage Nutritive Value.** Compromise between managing for yield and nutritive value is common to stockpiling programs. For example, bermudagrass yield in Texas increased by  $0.15 \text{ Mg ha}^{-1} \text{ d}^{-1}$  from day 14 through day 56 of stockpiling, but rate of decline for in vitro dry matter digestion (IVDMD) was  $2 \text{ g kg}^{-1} \text{ d}^{-1}$  (Holt and Conrad, 1986). Thus, the increase in yield with duration of stockpiling must be balanced with the decrease in nutritive value.

In West Virginia nutritive value of stockpiled tall fescue was greater for later initiation dates (Collins and Balasko, 1981b). In Nebraska delaying initiation of stockpiling of cool-season grasses from July to August increased IVDMD concentration and decreased NDF throughout the winter. Herbage CP of smooth brome grass in Minnesota increased and ADF and NDF decreased as initiation of stockpiling was delayed (Cuomo et al., 2005). In Ireland proportion of green leaf during winter in perennial ryegrass and ryegrass–white clover pastures was increased by delaying initiation of stockpiling, and this was accompanied by a decrease in stem and dead herbage (Hennessy et al., 2006).

In Missouri nutritive value of stockpiled annual ryegrass, small-grain rye, and tall fescue declined from December through March (Kallenbach et al., 2003a, 2003b). In North Carolina nutritive value of tall fescue was not affected by endophyte status during stockpiling initiated in mid-August and extending through February (Burns et al., 2006), but forage in vitro true digestibility declined linearly and NDF increased linearly as length of stockpiling period increased (Burns et al., 2006). Similarly, forage NDF of tall fescue and festulolium in Missouri increased and total digestible nutrients (TDNs) and CP of the

stockpiled forage decreased from November to March (Dierking et al., 2008). In vitro true digestibility of tall fescue in Missouri declined by 90 (year 1) and 50 (year 2)  $\text{g kg}^{-1}$  during the 84 d of stockpiling (Curtis and Kallenbach, 2007). Similar responses were observed with five cool-season grasses and white clover in Canada (Kunelius and Narasimhalu, 1993), perennial ryegrass and white clover in Ireland (Hennessy et al., 2006), three  $\text{C}_4$  grasses in Texas (Evers et al., 2004), bermudagrass in Arkansas (Scarborough et al., 2006), and limpograss in Florida (Quesenberry and Ocumpaugh, 1982).

**Pasture Performance Following Use for Stockpiling.** Early autumn initiation of stockpiling perennial ryegrass or ryegrass–white clover pastures in Ireland decreased tiller density in winter, and this effect persisted in spring (Hennessy et al., 2006). Initiation of new tillers in spring was inhibited in swards with high forage mass in autumn and winter due to shading at the shoot bases resulting in self-thinning.

In North Carolina persistence of tall fescue of varying endophyte status was not affected by length of the stockpiling period. Endophyte-free types had greater stand loss than endophyte-infected or novel-endophyte types, which were not different (Burns et al., 2006). White clover and orchardgrass were stockpiled in West Virginia (Belesky and Fedders, 1995). When stockpiling was initiated early, orchardgrass had fewer, larger tillers, and the clover had few growing points. Late initiation of stockpiling resulted in more clover than when initiated early.

**Effect of Endophyte Status on Stockpiled Forage.** Increasing level of endophyte infection (20%, 51%, and 89%) of stockpiled tall fescue in Missouri was associated with greater forage mass (4.35, 4.51, and  $4.95 \text{ Mg ha}^{-1}$ , respectively) during the grazing period. Also in Missouri, Kallenbach et al. (2003b) found mass of endophyte-infected fescue was 20% greater than for endophyte-free or nontoxic endophyte when harvested monthly from mid-December through mid-March. In North Carolina (Burns et al., 2006) and Arkansas (Flores et al., 2007), herbage mass of stockpiled tall fescue was not affected by endophyte status.

Novel endophyte and endophyte-free tall fescue stockpiled in Arkansas beginning in late summer and ending from December through February had similar DM and NDF disappearances (Flores et al., 2007). In Missouri, tall fescue with three levels of endophyte infection was stockpiled and grazed for 84 d starting 1 December (Curtis and Kallenbach, 2007). There was no effect of endophyte level on CP in either of 2 yr, whereas in vitro true digestibility was greater in 1 yr for the lowest endophyte level.

Following stockpiling of endophyte-infected tall fescue, total ergot alkaloid concentration was greatest at the beginning of the grazing period and decreased much faster than nutritive value during the period (Curtis and Kallenbach, 2007). It was recommended that low-endophyte pastures be grazed first and high-endophyte pastures last. This conclusion

was supported by additional Missouri research with stockpiled novel-endophyte, endophyte-free, and endophyte-infected tall fescue that was harvested monthly from mid-December through mid-March (Kallenbach et al., 2003b). Ergovaline was present only in toxic endophyte-infected tall fescue, but it declined by 85% from December through March.

### Seasonal Timing of Initiation, Termination, or Deferral of Grazing

Reasons for altering season of grazing or deferring grazing, other than stockpiling for out-of-season use, include increasing productivity, nutritive value, and persistence of the pasture or maintaining botanical composition, reducing weed invasion, improving water use, and improving wildlife food and habitat. Most related research was conducted in Europe, New Zealand, and Australia, but there is some US literature.

Switchgrass is an example of a warm-season grass that can provide grazing during periods when cool-season grasses are not productive. Including warm-season grasses in a grazing system can diversify the landscape and improve wildlife habitat. Photo by Lynn Betts, USDA-NRCS.





Alternative water sources may reduce time livestock spend in surface water bodies and improve animal health, water quality, and wildlife habitat. Photo by Chris Coulon, USDA-NRCS.

**Timing of Initiation.** Big bluestem in Nebraska was grazed in May when tillers were 15 to 20 cm tall or not grazed until late vegetative or early stem elongation stages (Mousel et al., 2003). Grazing in May did not reduce season-long pre-grazing forage mass, but pastures grazed at stem elongation in June had limited regrowth. Grazing first at vegetative instead of stem elongation stage resulted in greater seasonal leaf yields and allowed for grazing in both August and September. May grazing did not negatively affect persistence,

but root mass, area, and volume in the top 30 cm of soil were lowest in paddocks grazed first at stem elongation (Mousel et al., 2005). In Iowa delaying spring grazing of smooth bromegrass increased forage mass at turn out from approximately 800 to 2700 kg ha<sup>-1</sup>, but CP and IVDMD declined linearly as turn out was delayed.

Herbage mass was greater for perennial ryegrass in Ireland following late April vs. late March or early April turnout (Carton et al., 1989a). A greater proportion of smaller tillers during subsequent regrowth was associated with early defoliation and resulted in lower leaf extension rates (Carton et al., 1989b). In France early grazing of perennial ryegrass reduced subsequent pre-grazing herbage mass, but it increased sward nutritive value into the summer (O'Donovan and Delaby, 2008). Early turnout for timothy and tall fescue in Finland decreased pre-grazing herbage mass early in the growing season but not later (Virkajarvi et al., 2003). Reduced autumn regeneration of growth was observed in phalaris plants defoliated the previous spring at either early stem elongation or early boot stages (Culvenor, 1994). Avoidance of a heavy grazing during stem elongation in spring enhanced persistence when subsequent growth conditions were unfavorable due to dry weather.

**Timing of Termination.** Grazing perennial ryegrass, prairiegrass, and tall fescue swards every 30 d from August through November in Pennsylvania gave greater fall yield than grazing during September only, but the latter had greater spring yields than traditional stockpile and monthly grazing treatments (Hall et al., 1998). Greater tiller density in spring following grazing only in September resulted in greater spring yield for that treatment. In another Pennsylvania study on prairiegrass, spring yield decreased linearly as date of last defoliation the previous fall was delayed (Jung et al., 1994). Early fall harvest allowed time for replenishment of reserves prior to winter, but late fall harvest did not, especially when stubble was short. Tiller density in spring was greater for early than late fall defoliation.

In Quebec, Canada, autumn harvest of tall fescue taken after 15 September decreased ground cover and spring DM yield (Drapeau et

al., 2007). Harvesting or grazing tall fescue in the week preceding or following the first killing frost reduced spring growth and persistence. In Ireland delaying closure date of fall grazing of perennial ryegrass from 20 October to December decreased herbage mass through late May (Roche et al., 1996).

#### *Timing of Deferral (Other than Stockpiling).*

Deferral of grazing involves delaying onset of grazing or removing animals for a specific purpose before resuming grazing. Deferral of grazing of perennial ryegrass–white clover pastures in New Zealand throughout portions of the warm season increased annual herbage accumulation by 10% to 49% in the first year and 16% to 26% in the second (Harris et al., 1999). Deferral increased clover contribution, and amount of increase was positively related to duration of the deferral. The authors suggested that deferral resulted in lower soil temperatures and higher soil moisture that promoted survival of clover stolons and growing points. In New York white clover growth and recovery after grazing was poor following hot, dry weather in combination with grazing stress (Karsten and Fick, 1999). The authors recommended decreased grazing intensity during and for a short time after such weather events.

Humphrey and Patterson (2000) examined the question of how best to manage grazed pastureland in Scotland to promote biodiversity. Late summer grazing (early August to late September) was compared to no grazing, and species diversity declined with the no grazing treatment while it remained the same for the seasonal grazing treatment. The authors concluded that seasonal grazing was a useful management tool to promote plant biodiversity in pasturelands.

#### **Seed Production and Seedling Recruitment**

Grazing during the period of flowering and seed production has significant implications for seed production and seedling recruitment. Research on this topic is limited in the USA. In Florida seed yield of *aeschynomene* decreased when closure of autumn grazing was delayed (Sollenberger and Quesenberry, 1986). Maximum seed yields were achieved when autumn closure occurred 7 d to 14 d before first flower. Subsequent research showed that

discontinuing grazing at first flower or the week before was critical to achieving successful natural reseeding (Chaparro et al., 1991).

#### **Summary and Recommendations: Season of Grazing and Deferment**

Stockpiling extends the grazing season and reduces reliance on stored feed in many environments. In general, early initiation of stockpiling increases forage mass, but nutritive value is lower and duration of the regular grazing season on these pastures is shorter. Because weather conditions affect forage accumulation during autumn and impact both initiation and termination dates, choice of these dates is highly environment and forage species specific. In some environments, and with certain species, termination date is more flexible because mass and nutritive value of forage change relatively little during the late autumn through winter period. In other situations, termination date is critical because mass and nutritive value decrease rapidly after a defined date or period of stockpiling. Studies are limited on effects of stockpiling on subsequent stands, but early initiation of stockpiling to increase herbage mass during autumn and winter leads to decreased spring tiller density in some species.

The effect of endophyte status on forage mass and its ergovaline concentration must be considered when stockpiling tall fescue. In several studies, ergovaline declined rapidly in stockpiled endophyte-infected tall fescue during the late autumn and winter. Thus, other species or endophyte-free or novel-endophyte tall fescue should be grazed early in the utilization period, with endophyte-infected fescue grazed later after most ergovaline has dissipated.

Timing of initiation, termination, and deferral of grazing is important for maintaining cover and desired sward botanical composition. Relative to timing of initiation of grazing, most studies reviewed suggest a compromise between forage accumulation and nutritive value. Early turnout in spring often is associated with greater tiller production but lower forage mass at spring initiation that often carries over to subsequent grazing periods. Pastures grazed early after stockpiling have greater leaf percentage, less dead material, and greater



...ergovaline declined rapidly in stockpiled endophyte-infected tall fescue during the late autumn and winter.”



Efficiency of forage utilization can be increased by multispecies grazing due to less rejection of forage”

nutritive value. When termination date of fall grazing is important, its effect is often due to tiller dynamics or carbohydrate reserves.

Deferred grazing, other than stockpiling, has not been studied widely. Avoiding grazing during or immediately before a period of heat or drought stress is the most common practice described in the literature. There appears to be a need for research to more clearly delineate the effect of seasonality of grazing for the benefit of grassland management practitioners.

As need for high-quality forages in pastures increases, e.g., pasture-based dairying and grass-fattened beef, additional research into optimal timing of initiation, termination, and deferral of grazing is likely to be needed. There has been relatively little of this research done in the USA. The effects of timing of initiation of grazing on subsequent forage production and nutritive value, and the effects of timing of termination on persistence and regrowth suggest that this is an area that may benefit from increased research focus, especially when environmental responses are included.

#### **TYPE AND CLASS OF LIVESTOCK**

Different types of livestock have different physical characteristics, foraging strategies, and ingestive anatomy; thus it is expected their effect on pastureland will differ. This grazing strategy has received considerably less research attention than others addressed thus far. Only 15 papers described forage quantity, nutritive value, botanical composition, and plant persistence responses to type and class of livestock. Much of that literature focused on mixed grazing effects on plant responses, with fewer addressing type of livestock effects. No studies were found that compared plant responses to classes of livestock within a species.

#### **Differences in Ingestive Anatomy and Behavior among Ruminants and Horses**

Ruminants are commonly classified into feeding types based on ingestive anatomy and feed choices (Hofmann, 1989). Cattle and sheep are often categorized as “grazers” or “grass and roughage” eaters. Grazers have relative short lips, broad muzzles, and a cornified tongue that protects it during tearing of abrasive plant tissue (Van Soest, 1994). Goats are termed “intermediate feeders,” with some

characteristics of both “grazers” and “selectors.” Goats have a fairly narrow but deep mouth opening and mobile lips and tongue designed for selective ingestion of plants and plant parts including leaves and twigs of woody plant species (Van Soest, 1994).

Sheep have narrower mouths and a highly curved incisor arcade making them better suited anatomically for diet selection, including browsing, and grazing closer to ground than cattle (Walker, 1994), but sheep generally prefer grazing herbaceous material if quantity is not limiting (Benavides et al., 2009). Horses have mobile lips and a large mouth; they ingest forage by severing it between their upper and lower incisors. This mode of prehension causes horses to prefer shorter pasture than cattle, and horses are notorious spot grazers.

#### **Individual or Multispecies Grazing Effects on Plant Response**

Grazing two or more livestock species on the same land in a single growing season is known as dual use or multispecies grazing (Animut and Goetsch, 2008). Efficiency of forage utilization can be increased by multispecies grazing due to less rejection of forage due to dung contamination (Abaye et al., 1994), preference for particular species or plant parts, willingness to consume plants that are not preferred or would have adverse effects on the other animal species, and ability to gain access to forage (topography, terrain, or plant growth habit) that is not available to the co-grazing species. Because pastures often tend to be less species rich than rangeland, opportunities to take advantage of multispecies grazing may be fewer in pastureland than in rangeland.

**Forage Quantity.** In Virginia sheep grazed closer to cattle dung spots than did cattle to cattle dung spots, resulting in greater forage utilization and pasture uniformity in mixed-grazing pastures (Abaye et al., 1994). Lambs reached target weight sooner on mixed-grazing pastures, allowing earlier removal and avoidance of late-summer stress due to lack of available forage. Mixed cattle and sheep grazing alfalfa-orchardgrass pastures in Mexico promoted more homogeneous grazing than did cattle alone due to lower rejection of dung-contaminated forage (Mendiola-González et al., 2007).

The grazing behavior of different animal species also seems to be associated with observed differences in quantity of forage. In northwest Spain pastures grazed by cattle had taller mean height than those grazed by sheep (Benavides et al., 2009). Sheep were able to maintain their live weight at a lower sward height, and they grazed more intensively on the pasture area. In Australia a phalaris-subterranean clover pasture was grazed by cattle alone, sheep alone, or cattle + sheep (Bennett et al., 1970). Rank of forage mass was always cattle alone > cattle + sheep > sheep alone. Similarly, in alfalfa-orchardgrass pastures in Mexico, forage mass was lower and sward height shorter when lambs grazed alone than for heifers, and mixed grazing was intermediate. In ryegrass-white clover pastures in northern Spain, swards where goats grazed last had greater forage mass because goats grazed taller, non-grazed material and clumps, leading to more

uniformly high growth rates (del Pozo et al., 1998).

In summary, research assessing the effect of different livestock species on forage mass is limited. The most consistent response has been that forage mass or sward height is less on pastures grazed by sheep than on those grazed by cattle or goats. An experimental issue of concern for studies comparing mono- and mixed-species grazing is equalizing stocking rates among treatments. Failure to do so greatly limits the value of the research.

**Forage Nutritive Value.** Minimal research addresses the effect of type of livestock grazing on nutritive value of pastureland. In Virginia, Kentucky bluegrass and white clover pastures were grazed by cattle, sheep, or both, and trends in nutritive value were not consistent (Abaye et al., 1994). In some cases, nutritive value responses can be inferred based on

Shade can be a powerful attractant to livestock when temperatures are high, affecting livestock and manure distribution in the landscape. Photo by Carmen Agouridis, University of Kentucky.





Uncontrolled access of livestock to surface water bodies can negatively affect livestock health, water quality, and wildlife. Photo by Carmen Agouridis, University of Kentucky.

changes in botanical composition. White clover contribution increased in perennial ryegrass–white clover swards grazed by goats vs. sheep in Scotland (del Pozo et al., 1997) or grazed most recently by goats vs. sheep in Spain (del Pozo et al., 1998). In the latter case, grass stem and dead proportion were lower when pastures were grazed most recently by goats, and these differences would also be consistent with greater nutritive value on pastures grazed by goats than by sheep. Improvement in animal performance for both goats and steers followed shifts in botanical composition associated with multispecies grazing (Donaldson, 1979).

**Forage Botanical Composition and Persistence.** The majority of studies have assessed effects of type of livestock on botanical composition. Two common themes emerge. Goats or, to a lesser extent, sheep can reduce shrub and brush cover in abandoned or invaded pastureland, and a consistent pattern is seen of reduction in legume or forb composition of pastures associated with grazing by sheep relative to other grazers.

In Virginia pastures grazed by sheep (alone or with cattle) had at least 10 percentage units more bluegrass than when cattle grazed alone, five to seven percentage units less white clover, and three to six units less forbs (Abaye et al., 1997). They concluded sheep preferred broadleaf plants, both legumes and forbs, and sheep in mixed-grazing pastures

affected composition similarly but to a lesser extent than sheep alone. In Australia, after 3 yr of grazing a phalaris–subterranean clover pasture, percent clover was 57%, 46%, and 36%, respectively, for cattle, cattle and sheep, and sheep alone (Bennett et al., 1970).

They concluded that clover benefited from cattle grazing because they consumed more grass stems and dead material than sheep, encouraging growth of clover. In an extensive review of United Kingdom grazing literature on mesotrophic “old meadow” pasture, Stewart and Pullin (2008) found support for the conclusion that sheep grazing can result in lower forb diversity than cattle grazing, especially at high stocking rates.

In northern Spain swards had higher live clover percentage and lower dead and grass stem proportions where goats grazed last than where co-grazed or sheep grazed last (del Pozo et al., 1998). The authors suggested goats were better able to deal with reproductive and senescent grass material and grazed it to lower residual heights. Studies in Scotland and New South Wales, Australia, showed the proportion of clover was greater with goat grazing than with sheep grazing (del Pozo et al., 1997; Holst et al., 2004).

In North Carolina overgrown hill land pasture (most prominent species were Kentucky bluegrass, tall fescue, and white clover) was not grazed, grazed by goats alone, or grazed by both goats and cattle to determine their effectiveness in reclaiming areas overgrown with invading herbaceous weeds and woody species (Luginbuhl et al., 1999). During the course of four grazing seasons, goats grazing alone or with cattle effectively shifted botanical composition of overgrown hill land pastures toward desirable forage species and controlled encroaching multiflora rose. In northern Spain, one-third of the treatment area was perennial ryegrass–white clover pasture and the remainder was shrubland (Benavides et al., 2009). Goats were more intentional in browsing than sheep and cattle, and mixed grazing with goats slowed brush encroachment and increased growth of herbaceous plants. In New South Wales, Australia, goats were an effective control strategy for nodding thistle in tall fescue–perennial ryegrass–white clover–subclover pastures (Holst et al., 2004).

### Summary and Recommendations: Type and Class of Livestock

No evidence was found that breed or age of a particular species has significant effects on pasture characteristics, but species of livestock is important. Livestock species have minimal effect on forage quantity and nondocumented effects on forage nutritive value, but important and well-documented effects on botanical composition and persistence. The literature verifies that co-grazing or grazing by particular species can be used to manipulate botanical composition of pastures and that selection of livestock species is an important prescribed grazing tool for maintaining legumes in pastures and ridding swards of invasive, unwanted, or potentially toxic plants. Further research is needed, however, because studies to date have been relatively limited both geographically and in the forage species tested. In addition, most research is from outside the USA, leaving a significant gap in determining the potential of using particular livestock species or mixed grazing in the USA.

Stocking rate is a key consideration when comparing grazing by different types and classes of livestock, but choice of livestock species can be an excellent tool for improving vegetation condition. The literature consensus is that choice of animal species is less critical than grazing intensity, but more research is required to fully understand animal species-grazing intensity interactions (Stewart and Pullin, 2008).

### DISTRIBUTION OF LIVESTOCK IN THE LANDSCAPE

Factors affecting livestock distribution on pastureland include position of water and shade, proximity to barns, topography, and feed sources (Mathews et al., 1996). As cattle frequent an area, they affect plants and soil and may influence water quality and quantity as well as riparian and watershed function (CAST, 2002). Much of the literature on livestock distribution focuses on water impacts. However, a total of 13 papers did specifically address plant responses. Major areas of discussion included the effect of topography, paddock size, and position of shade and water on forage mass and species composition.

### Topography

On hill-country pastures in New Zealand, approximately 60% of dung accumulated in flat areas (hill summits or bottoms of slopes), and the proportion of dung in the remainder of the pasture decreased as slope increased (Rowarth et al., 1992). Deposition of dung is closely associated with time spent in a portion of the landscape (Dubeux et al., 2009), implying animals spent more time in flat areas. The literature does not allow separation of the effects of topographic distribution of livestock from the inherent characteristics (e.g., soil fertility, drainage, aspect) of a portion of a landscape. However, numerous studies describe topographic differences in plant responses under grazing.

A series of studies were conducted on cool-season grass pasture (smooth brome grass, Kentucky bluegrass, and reed canarygrass dominated) in Iowa that was overseeded with legumes. Summit (top, 0–5% slope), backslope (middle, 10–24% slope), and toeslope (bottom, 0–5% slope) landscape positions were compared under continuous and rotational stocking at the same stocking rate. Forage mass was greatest on toeslope positions (Harmon et al., 2001), and legume mass, proportion, richness, and diversity showed increasing trends at backslope positions compared with summit or toeslope. Sloping sites had greater numbers of species than flat sites. Shannon's Diversity Index was greater for sloping vs. flat areas and was ranked continuous > rotational > non-grazed (Barker et al., 2002). Species richness within grazed pastures was greatest on backslope positions, and species diversity was limited at summit and toeslope by grass competition (Guretzky et al., 2005). Legumes tended to be greatest and weeds least on backslope and with rotational stocking.

Also in Iowa, legume percentage cover increased as a function of slope, and the rate of increase was greater for rotational than continuous stocking and both were greater than non-grazed (Guretzky et al., 2004). Legumes were most successful at 15% to 20% slope. Success of legumes at these slopes was associated with less competition from grasses than at summit or toeslope, and competition from grasses was greatest where soil moisture was highest. No data were reported on



...co-grazing or grazing by particular species can be used to manipulate botanical composition of pastures”



Reducing  
paddock size  
produces greater  
evenness of  
forage use within  
paddocks...”

proportion of time spent by livestock at various slopes, so it is not clear if varied grazing time played a role in the response. In southeast Queensland, Australia, slope position had relatively minor effects on species richness, but there was evidence of less diversity in more fertile areas, perhaps comparable to toeslopes in Iowa (McIntyre and Martin, 2001). In Israel wetland sites had significantly lower richness of annual legumes compared with upland sites (Noy-Meir and Kaplan, 2002), perhaps again associated with greater competition from well-adapted grasses in wetland areas.

### Paddock Size

Patch grazing contributes to grassland degradation, even at low stocking rates (Barnes et al., 2008). Norton (2003) hypothesized that livestock in smaller paddocks or at higher stocking densities are more evenly distributed and access more forage. Reducing paddock size produces greater evenness of forage use within paddocks by limiting area available at one time and forcing grazing to occur more widely across the landscape as a whole (Hart et al., 1993). Making more effective use of pasture resources by distributing grazing more widely and uniformly across the landscape is an effective strategy for increasing livestock productivity (Hunt et al., 2007).

### Proximity to Shade, Water, or Structures

In a diverse pasture landscape in northern Germany, grazing sites with a shorter distance to a water trough or pond were preferred by cattle, while sheep preferred grazing close to their shed (Putfarken et al., 2008). In the Northern Territory of Australia, installing additional water points in large paddocks improved uniformity of grazing distribution, and providing shade, especially away from water points, induced livestock to use more areas in the pasture (Hunt et al., 2007). In Alabama relief from heat stress was the major factor in habitat-use decisions by cattle during the warm season (Zuo and Miller-Goodman, 2004). At this location, livestock stood in surface water bodies, because of their cooling potential, even when alternative water and shade sources were provided.

Changes in soil N, phosphorus (P), and potassium (K) were compared around shade

and water sources in rotationally stocked kikuyugrass pastures in Hawaii (Mathews et al., 1999). Based on the magnitude of increases in soil nutrient concentration, the authors concluded that excreta deposition was greater around shade than water and that shade sources had a greater effect than water sources on distribution of cattle in the landscape.

In 0.33- to 1-ha bahiagrass pastures in Florida that were continuously stocked, herbage accumulation rate was 40, 33, and 20 kg ha<sup>-1</sup> d<sup>-1</sup>, respectively, in zones that were less than 8 m (zone 1), 8 to 16 m (zone 2), or > 16 m from shade or water (Zone 3) (Dubeux et al., 2006). Response was due in part to greater accumulation of soil nutrients in zone 1. Herbage mass in the three zones was 2410, 2900, and 3030 kg ha<sup>-1</sup>, respectively. This was associated with greater time spent by animals in zone 1 and corresponding reduction in forage mass. In the lowest of three management intensity treatments, forage N, P, and in vitro digestion were greater in zone 1 than zone 3, likely because of greater nutrient deposition via excreta in zone 1, and also because of greater resident time by animals, resulting in more frequent visits to a given patch with less mature forage.

### Summary and Recommendations: Distribution of Livestock in the Landscape

There is sparse literature describing plant responses to livestock distribution. Within rolling topography, it is difficult to separate the effects of livestock distribution from those of aspect, soil fertility, and drainage. In general, sloping areas are thought to have shorter grazing time, greater species richness, greater legume proportion, and less herbage accumulation than summit or toeslope areas. These differences might serve to influence subsequent grazing behavior and time spent in various regions of the pasture, but this has not been quantified.

Shade and water are other major factors affecting livestock distribution. Shade seems to have a greater impact on livestock distribution than does location of water source, particularly during warm seasons or in warm climates. There is evidence that subdividing large grazing units into smaller paddocks

decreases heterogeneity in forage mass and amount of overgrazed areas within the pasture. Further, increasing the number of watering points in conjunction with decreasing pasture size may minimize spot grazing and reduce associated stand deterioration. These management interventions could be considered as part of a prescribed grazing plan in large pastures.

## PURPOSE 2: IMPROVE OR MAINTAIN QUANTITY AND QUALITY OF FORAGE FOR GRAZING AND BROWSING ANIMALS' HEALTH AND PRODUCTIVITY

### Grazing Intensity

A rich literature describes the nature of the relationship between grazing intensity and animal productivity. Because of complexities and costs associated with research utilizing reproductive livestock, most of this work has been conducted with growing animals. Because the fundamental relationships between grazing intensity and nutrient harvest do not vary among classes of livestock, and because animal growth rates often provide a more sensitive measure of production responses than changes in body energy stores or reproductive rates, the bulk of the literature relies heavily on results from studies with growing animals.

There is broad agreement that increasing grazing intensity, typically measured as stocking rate (animal units  $\text{ha}^{-1}$  for a grazing season), results in a decrease in performance of individual animals. The nature of this decrease, however, has been the subject of considerable discussion in the literature. A review by Hart (1993) describes several models of the stocking rate-gain response curve. Generally, on a given forage base, there is a critical stocking rate below which gain per animal is either unaffected or may increase slightly with increasing stocking rate. Models differ in their description of the gain per animal response above this critical stocking rate. Specifically, the decrease in gain per animal with increasing stocking rate has been described as linear with no threshold (e.g., Hart, 1978), or curvilinear with a concave (e.g., Mott, 1960) or a convex (e.g., Petersen et al., 1965) response surface (Fig. 3.3).

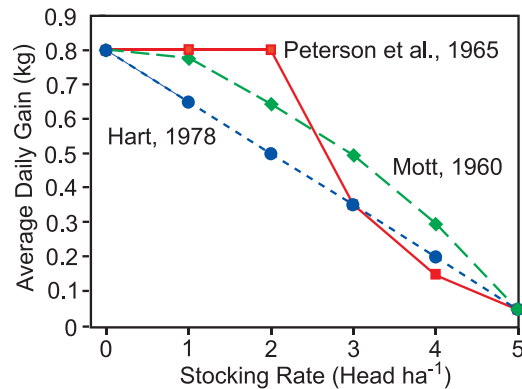


Even if the linear model is an oversimplification of the true biology of the association, it appears to adequately describe the response in the majority of studies in the literature. Thus, in this synthesis, various studies have been summarized with respect to the parameters of a threshold model in which gain is relatively unaffected at low stocking rates and declines in a linear fashion with increasing stocking rate.

Stimulated by the CEAP effort, and to better understand the effect of stocking rate on animal response, a comprehensive assessment of the relationship was undertaken across a large number of studies in the literature (Sollenberger and Vanzant, 2011). Because of the wide variation in individual animal weights in various studies, it was not adequate to describe stocking rates in terms of numbers of animals per unit area. Thus, stocking rates were described in  $\text{kg live wt ha}^{-1}$ , and these values were based on live weight at the beginning of the grazing season (i.e.,  $\text{kg initial live weight ha}^{-1}$ ). The influence of stocking rate was also evaluated as a function of metabolic body weight ( $\text{wt}^{0.75}$ ).

The data included were obtained from non-rangeland US studies published in refereed journals over the last 48 yr. Two nonrefereed studies (Gerrish, 2000; Vanzant, 2010) were included to provide data from underrepresented geographical regions and because all of the essential data were available.

Livestock access to streams can cause stream widening, reduced water depth, and increased water temperature, all of which negatively affect wildlife habitat. Photo by Carmen Agouridis, University of Kentucky.



**FIGURE 3.3.** Models proposed to describe the response of average daily gain to increases in stocking rate include linear (e.g., Hart, 1978), curvilinear with a concave response surface (e.g., Mott, 1960), or a plateau followed by a convex response surface (e.g., Petersen et al., 1965).

The majority of the studies utilized growing beef cattle and reported rates of gain as affected by grazing intensity.

To provide a response criterion that could be quantitatively analyzed, average daily gain within each study was regressed on stocking rate, providing both a  $y$ -intercept and a slope value for each study. These  $y$ -intercept and slope data constituted the parameters for a subsequent meta-analysis. A multiple regression approach was used to evaluate the influence of several factors on the slope of the average daily gain response to stocking rate. From the 26 independent reports, 58 observations (treatment  $\times$  year combinations) were included in the multiple regression analysis. More detail on this procedure is provided by Sollenberger and Vanzant (2011).

A four-variable model was derived using all 58 observations, which accounted for 69% of the variation in slope of the average daily gain response to stocking rate. Fifty-six percent of the variation in the slope of the response was attributable to differences in the  $y$  intercept of average daily gain. Thus, from this data set, the strongest predictor of the slope of the average daily gain response to increasing stocking rate was the estimate of gain at a theoretical “zero stocking rate.” The greater the estimated gain of cattle at low stocking

rates, the more rapid the decrease in average daily with increasing stocking rate.

Any factor that leads to greater forage quality, and thus increases intake, will increase the rate at which forage is removed at a given stocking rate. Similarly, an increase in stocking rate ultimately accelerates the decrease in average daily gain. Much smaller, but significant, portions of the variation were explained by the presence of grass and/or legumes. Little difference was seen in the effect of grazing intensity on ADG between alfalfa and “grass-only” pastures, but the effect was greater in mixed grass-legume stands. The relationship between grazing intensity and animal performance is likely more complex in mixtures than in monocultures because of variable effects of grazing intensity on the responses of the different species. The analysis also showed that at higher latitudes, an increase in stocking rate caused a smaller reduction in ADG than did a similar increase in stocking rate at lower latitudes.

Occasional reports are found of improved animal performance with increased grazing intensity (Bryan and Prigge, 1994; Fike et al., 2003; Burns and Fisher, 2008). In general, such improvements occur when forage mass is sufficient to allow ad libitum intake and diet nutritive value to increase as grazing intensity increases. Within the range of stocking rates typically studied, however, the negative influence of increasing grazing intensity on individual animal performance appears to be caused by reduced forage intake due to decreasing forage mass, and the slope of the ADG response to stocking rate becomes even more negative as forage nutritive value increases.

The relative roles of forage quantity and nutritive value were determined to be as follows: Forage nutritive value sets the upper limit for individual animal response (e.g., average daily gain), the slope of the decline in daily gain with increasing grazing intensity, and the “critical” forage mass at which the decline in daily gain begins. Forage quantity determines the proportion of potential daily gain response that actually will be achieved from a defined forage. Further, it is the primary driver of the direction of the daily

gain response (negative) to increasing grazing intensity (Sollenberger and Vanzant, 2011).

### Summary and Recommendations: Grazing Intensity

This literature synthesis supports the overriding importance of grazing intensity in determining animal performance on pasture. As was concluded for plant response, choices of stocking rate or sward stubble height are the most critical decisions affecting animal performance on grazed pastureland. The initial focus of prescribed grazing recommendations for maintaining quantity and quality of forage for health and productivity of grazing and browsing animals should rest squarely on implementing the proper grazing intensity.

### STOCKING METHOD

The relative benefits of different stocking methods to animal production continue to be debated. Primary interest in stocking methods stems from the desire to improve the productivity and sustainability of pasture-based livestock production systems. Differences among stocking methods could occur due to 1) maintaining more productive or higher-quality forage species, 2) increasing forage accumulation rate, 3) increasing the percentage of available forage mass that is consumed by limiting animal selectivity, or 4) ensuring more uniform animal distribution across the pasture. Much popular literature suggests that stocking method, and, in particular, rotational stocking, can improve animal production from pasture-based livestock production systems. This assertion will be evaluated.

Recently Briske et al. (2008) published a comprehensive review of the scientific literature dealing with the implementation of rotational stocking on rangelands. Among their conclusions was that "The experimental evidence indicates that rotational grazing is a viable grazing strategy on rangelands, but the perception that it is superior to continuous grazing is not supported by the vast majority of experimental investigations."

Our goal was to conduct a similar analysis of the pastureland literature to determine what conclusions it supports about stocking methods. The 19 papers published in refereed journals from US research included 29 separate

comparisons of gain per animal response and 26 of gain per ha response on continuously and rotationally stocked pastures (Table 3.4).

Sixty-six percent of experiments (19 of 29) showed no difference in gain per animal between rotational and continuous stocking, 24% (6 of 29) showed continuous greater than rotational, and 14% (4 of 29) showed rotational greater than continuous (Fig. 3.4). Thus, the literature suggests that in most situations no difference is found among stocking methods in gain per animal. This is consistent with and follows the lack of conclusive evidence for an effect of stocking method on forage nutritive value, as reported earlier in this chapter.

With 26 observations, 69% (19 of 26) showed no difference in gain per ha between continuous and rotational stocking (Fig. 3.5). Gain per ha was greater for rotational than continuous stocking in 27% of observations (7 of 26), while continuous was greater than rotational in only 4% (1 of 26). Earlier in the chapter it was noted that 85% of studies comparing rotational and continuous stocking showed forage quantity advantages for rotational stocking. Thus, the question arises: Why would 85% of studies report rotational stocking has a forage quantity advantage, but only 27% report greater animal gain per ha?

One issue that merits attention is experimental methodology, especially whether the experiment was conducted using the same or variable stocking rates. When responses to stocking method of gain per animal and gain per ha were sorted based on whether stocking rate was the same or variable, the response of average daily gain was similar across methods (62% showed no difference for same stocking rate experiments vs. 69% for variable; Fig. 3.4). However, when gain per ha was measured, 92% of same stocking rate studies showed no difference between methods, while variable stocking rate studies showed no difference in 50% of cases (Fig. 3.5).

Why might this occur? Gain per ha is a function of average daily gain and stocking rate. When stocking rate is fixed at the same level on both continuous and rotational treatments, difference in gain per ha can only occur due to



...literature synthesis supports the overriding importance of grazing intensity in determining animal performance on pasture."

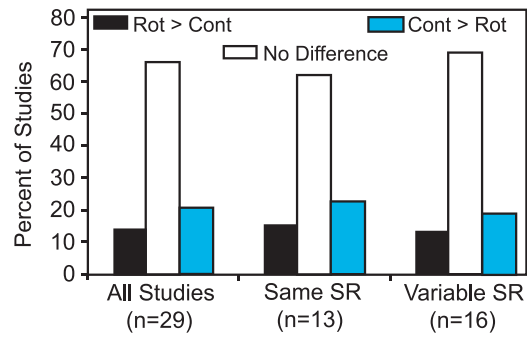
**TABLE 3.4.** Summary of experiments evaluating animal responses to continuous and rotational stocking.<sup>1</sup>

Forage type <sup>2</sup>	Location	Animal species <sup>3</sup>	Animal class <sup>4</sup>	Length of trial, years	No. of pasture replicates	
Irrigated alfalfa–tall wheatgrass	Tucumcari, NM	B	G	2	2	
Bahiagrass	Brooksville, FL	B	G	3	2	
Smooth brome–reed canary grass–quackgrass–timothy–Kentucky bluegrass	Ste. Anne de Bellevue, QC	B	DO	2	2	
Bermudagrass/-wheat- legume mix	Parsons, KS	B	DO	3	2	
Bermudagrass–E(+) tall fescue	Eatonton, GA	B	G	2	3	
Bermudagrass–wheat–annual ryegrass	Booneville, AR	B	G	2	2	
Tall fescue–orchardgrass–clover	El Dorado Springs, MO	B	G	1	2	
Bahiagrass	Brooksville, FL	B	DO	3	2	
Bermudagrass–E(–) tall fescue	Eatonton, GA	B	DO	3	2	
Alfalfa–meadow brome–Russian wild ryegrass	Brandon, MB	B	G	4	2	
Italian ryegrass	Jeanerette, LA	B	G	1	4	
Alfalfa–orchardgrass	Bozeman, MT	O	E	2	2	
			L			
Bermudagrass	Gainesville, FL	B	G	2	3	
Old world bluestem	El Reno, OK	B	G	2	2	
Alfalfa–tall fescue–orchardgrass	Baylis, IL	B	G	2	2	
E(+) tall fescue–ladino clover	Springfield, TN	B	DO	4	2	
E(+) tall fescue	Parsons, KS	B	G	1	2	
E(+) tall fescue–ladino clover						
Bromegrass	Clay Center, NE	B	G	1	2	
				1		
Coastal Bermudagrass	Tifton, GA	B	G	3	4	

<sup>1</sup>Comparisons between rotational (R) and continuous (C) stocking in livestock production (both on individual animal and per-hectare basis) are shown in the last two columns. R = C indicates that no significant differences were found between stocking methods; R > C, that response to rotational stocking was greater than response to continuous stocking; and C > R, that response to continuous stocking exceeded that of rotational stocking. <sup>2</sup>E(+) indicates endophyte-infected tall fescue; E(–), endophyte-free tall fescue. <sup>3</sup>B indicates bovine; O, ovine. <sup>4</sup>G indicates growing; DO, dam and offspring; E, ewes; and L, lambs. <sup>5</sup>V indicates variable stocking rates (different stocking rates used for continuously and rotationally stocked treatments); S, same stocking rate was used for continuous and rotational stocking. <sup>6</sup>Multiple stocking rates were compared within each stocking method. <sup>7</sup>Phillip et al. (2001) analyzed and reported responses separately

	No. of paddocks in rotation	Pasture size, ha	Stocking rate strategy <sup>5</sup>	Livestock production		Reference
				Per head	Per hectare	
	5	1.3 to 1.6	V	R = C	R = C	Lauriault et al., 2005
	4	16	S	R = C	R = C	Willms et al., 2002
	6 and 9	1.8 to 2.7	S <sup>6</sup>	R = C <sup>7</sup>	R = C <sup>7</sup>	Phillip et al., 2001
	8	4.0	S	R = C	R = C	Lomas et al., 2000
	8	0.81	V	R = C	R = C	Kuykendall et al., 1999b
	3 and 11	0.68	V	R = C <sup>8</sup> R = C	R > C <sup>8</sup> R = C	Aiken, 1998
	4	0.81	S	R = C	R = C	Lehmkuhler et al., 1999
	2 and 3	16	S	R = C	R = C	Hammond et al., 1997
	12	16	V	R = C	R > C	Hoveland et al., 1997
	10	3.7	S <sup>9</sup>	C > R <sup>9</sup> R > C at low SR C > R R > C at high SR	R = C <sup>9</sup> R = C R = C R > C at high SR	Popp et al., 1997a
	3	3.9	V	C > R	R > C	Hafley, 1996
	8	1.6	V	R > C  Y1: C > R Y2: R = C	Y1: R = C Y2: R > C  R = C	Thomas et al., 1995
	3 and 15	0.3	V	R = C	R = C	Mathews et al., 1994b
	2	1.8	V	R = C <sup>10</sup> R = C R > C	R = C	Volesky et al., 1994
	6 and 11	2.5 to 4.5	V	R = C	R > C	Bertelsen et al., 1993
	7	6.5 to 11.3	S	R = C	R = C	Chestnut et al., 1992
	10	2.0	S	R = C C > R	R = C	Coffey et al., 1992
	8	16.2	S	R = C		Jung et al., 1985
			V	R = C	R > C	
	4	0.33	V	C > R	C > R	Hart et al., 1996

within each month of the grazing season. Values represent average responses across the entire grazing season, based on interpretation of their reported monthly responses and SE. Additionally, responses only represent calf gains. Cow weight changes, though reported by the authors, were excluded from this analysis because of the difficulty in associating these data with economic returns. <sup>8</sup>In Aiken (1998), responses were reported separately for the cool-season, and warm-season phases of the study. Upper values refer to the cool-season phase; lower values to the warm-season phase. <sup>9</sup>In Popp et al. (1997a), responses were analyzed and reported separately within each year from year 1–4 in order from top to bottom. <sup>10</sup>In Volesky et al. (1994), responses were reported separately for early, mid-, and late season from top to bottom, respectively. Response to stocking method was similar for both SRs if SR response is not indicated.



**FIGURE 3.4.** Comparison of rotational stocking (Rot) and continuous stocking (Cont) on average daily gain by grazing livestock. The 29 studies (all studies) were divided into those for which stocking rate was the same for both stocking methods (same SR) and those for which stocking rate was varied for both stocking methods based on some measure of forage height, mass, or allowance (variable SR).

differences in average daily gain. It has already been shown that rotational and continuous stocking rarely differ in average daily gain within the typical range of stocking rates used in most grazing experiments, so it is logical that experiments using the same stocking rate for both continuous and rotational stocking rarely show differences in gain per ha (Fig. 3.5).

In contrast, when a variable stocking rate is used, the researcher adjusts stocking rate periodically to maintain a specific pasture characteristic at the same level on both treatments. If one stocking method results in greater forage accumulation or more efficient utilization of forage mass, then increased stocking rate is needed on that treatment in order to maintain the same sward state. This may allow greater gain per ha to occur on pastures with greater forage accumulation or higher efficiency of utilization of forage mass, even if average daily gain is not different between treatments.

An important limitation of most research comparing stocking methods at the same stocking rate has been that only one stocking rate was imposed. The same stocking rates can be used effectively to compare stocking methods if animal performance response is measured at a range from quite low to quite high stocking rates. If forage quantity is greater on rotational pastures, then the

relative advantage in production per animal for rotationally stocked pastures is expected to be small or nonexistent at low stocking rates but measurable at high stocking rates. This occurs because at high stocking rates the quantity advantage of rotational stocking has greatest impact on individual animal performance. Studies using this approach show advantages in average daily gain for rotational stocking at high stocking rates (Popp et al., 1997a; Gerrish, 2000).

### Summary and Recommendations: Stocking Methods

We conclude that average daily gain in the short term is generally not affected by stocking method, but in the long term, species composition may change with time due to stocking method and thus affect animal response. Most pastureland grazing trials are conducted for time periods of 3 yr or less that are not long enough to account for changes in species composition. The effect on gain per ha is less clear and appears to be confounded with grazing trial methodology. Studies that adjust stocking rate based on forage mass or forage allowance can account for differences in forage accumulation or efficiency of utilization of forage mass and are more likely to detect differences in gain per ha due to stocking method. Differences occurred in about 50% of the variable stocking rate studies, and in most cases rotational stocking was favored.

Results of this pastureland review are in general agreement with those found by Briske et al. (2008) for rangeland, with the exception that the likelihood appears to be greater for an advantage in gain per ha for rotational stocking of pastureland than rangeland. One conclusion of Briske et al. (2008) was that “a continuation of costly grazing experiments adhering to conventional research protocols will yield little additional information.” We agree that additional animal performance studies comparing stocking methods are unlikely to add significantly to our knowledge of plant and livestock responses *unless* special attention is given to specific sampling protocols and the studies are of greater duration. Additionally, these types of studies are warranted if they are done in conjunction with soil, water, and wildlife collaborators so that a more comprehensive set of longer-term responses can

be quantified, including many responses for which we currently have limited data.

One striking difference for pastureland studies (Table 3.4) and those reported for rangeland (Briske et al., 2008) is the longest pastureland study was 4 yr, but most rangeland studies were at least 5 yr, with some extending as long as 25 yr. This is important because 1) environmental conditions can interact with grazing management such that multiyear studies are necessary and 2) management influences on pasture productivity are often cumulative across years. For example, increased gain per ha in a given year may be achieved simply by increasing stocking rate, which may not be sustainable over the long term. Likewise, strategies that improve plant health and vigor may take several years to result in appreciable increases in pasture productivity.

Finally, benefits of rotational stocking have been the subject of much controversy over the years, and this conversation is likely to continue. Our assessment suggests that the greatest impacts of the choice of stocking method are likely to be number of animals that can be supported on the pasture and, in the long term, the species composition of the sward. These effects are important, but in our judgment are less important than proper management of grazing intensity by the land manager. Thus, the starting point in developing prescribed grazing practices for benefiting animal health and production is to understand the achievable goals for use of the available resources and then optimizing grazing intensity to accomplish them for the desired time period.

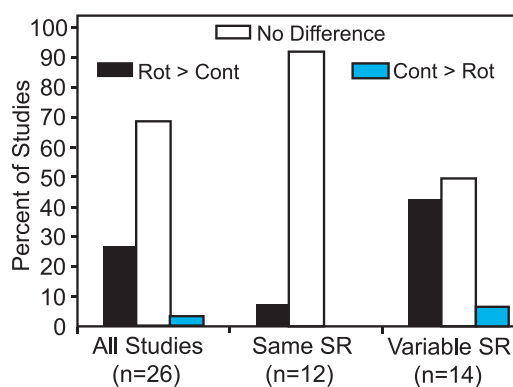
### SEASON OF GRAZING AND DEFERMENT

Throughout much of the central and eastern USA, a variety of options are available to extend the grazing season. Somewhat surprisingly, however, a paucity of information is encountered in the literature regarding animal performance responses to season of forage use. The main systems that incorporate season of use as a primary factor are stockpiled and complementary forage systems, particularly those designed to utilize both cool- and warm-season forage species during the pasturing season.

### Stockpiled Forage Systems

A long-accepted management practice (Taylor and Templeton, 1976) of stockpiling tall fescue is the most common strategy for extending the grazing season in mid-latitude states of the Midwestern and eastern USA (Collins and Balasko, 1981b). Utilization of stockpiled forages represents a substantial reduction in feed costs compared with harvested forages because there is no need for mechanical harvesting and handling (Hitz and Russell, 1998; Lalman et al., 2000). There is evidence that livestock performance on grazed, stockpiled forages exceeds that of the same forages when harvested (Allen et al., 1992a). Cows grazing stockpiled tall fescue–alfalfa or smooth bromegrass–red clover in Iowa were able to maintain greater or equal body weight and condition scores, but consumed between 1030 and 1070 fewer kg cow<sup>-1</sup> of stockpiled forage than cows in drylot (Hitz and Russell, 1998). They attributed this partly to improvements in diet quality afforded by opportunities for selective grazing within the stockpiled, as compared with the harvested forages.

One potential mitigating factor with respect to livestock response on stockpiled tall fescue is the degree of endophyte infestation. Indeed, part of the interest in using tall fescue for fall/winter forage in stockpiled systems is the recognition that endophyte toxicity will



**FIGURE 3.5.** Comparison of rotational stocking (Rot) and continuous stocking (Cont) effects on gain per ha by grazing livestock. The 26 studies (all studies) were divided into those for which stocking rate was the same for both stocking methods (same SR) and those for which stocking rate was varied for both stocking methods based on some measure of forage height, mass, or allowance (variable SR).

be less in cooler seasons. However, results of studies evaluating the influence of endophyte presence in stockpiled fescue systems are mixed. Endophyte presence decreased gains of steers grazing stockpiled fescue (Beconi et al., 1995), and cows with calves lost weight more rapidly when grazing stockpiled tall fescue with high (89%) than with low (20%) endophyte levels (Curtis and Kallenbach, 2007). However, in both of these studies, differences were ameliorated after cattle were removed from tall fescue and the experimental groups were treated similarly.

No effect of endophyte infestation level was detected for calf gain, either during or subsequent to the stockpile phase (Curtis and Kallenbach, 2007). Similarly, average daily gain of growing cattle was similar when grazing endophyte-free, endophyte-infected, or novel-endophyte stockpiled tall fescue in winter (Drewnoski et al., 2009). However, animal grazing days and weight gain per ha were greater with endophyte-free tall fescue than with either of the other forages. In Georgia average daily gain of yearling heifers grazing endophyte-infected tall fescue was lower than when grazing novel-endophyte tall fescue in autumn through spring, but equal in summer (Franzluebbers et al., 2009). Due to seasonal changes in stocking density, gain per ha was lower with endophyte-

infected than with novel-endophyte tall fescue in spring and autumn only, and was greater with endophyte-infected tall fescue in the summer.

Based on limited data from supplementation studies of cattle grazing stockpiled tall fescue, protein is not limiting for beef cattle production. In a study using a supplement of either nondegraded protein or an isocaloric control for primiparous heifers on stockpiled tall fescue, the body condition score, body weight, calf weight, milk production, and postpartum interval were not affected (Strauch et al., 2001). Improved weight gains and body condition scores of heifers grazing stockpiled endophyte-infected tall fescue were achieved by supplementing with whole cottonseed (Poore et al., 2006), but these responses were likely due to energy from the cottonseed, rather than to protein.

Though considerable research has been done on the quality and forage yield of other forages for stockpiled fall and/or winter grazing (Davis et al., 1987; Lalman et al., 2000; Misleve and Martin, 2007; Dierking et al., 2008), a lack of information is seen in the refereed literature on animal responses with these forages.

### Complementary Forage Systems

Complementary forage systems are those that capitalize on forages having yield and forage quality distributions different from the dominant forages in a region. Thus, in regions in which warm-season grasses dominate, cool-season species are utilized to extend the grazing season and increase animal production (Vogel et al., 1993; Moore et al., 1995; Fontaneli et al., 2000; Volesky and Anderson, 2007). Alternatively, warm-season forages are often planted to complement dominant cool-season species that have low productivity in summer (Belesky and Fedders, 1995).

Improvements in cow-calf productivity and enterprise profitability have been observed when cultivated pastures, double-cropped with cool- and warm-season species, were included in a bermudagrass-based forage system (Bagley et al., 1987). In a comparison of four different year-long forage systems for stocker cattle production based primarily on cool-season species, improved gain was seen per ha and per

Varying herbage mass and color of "Wrangler" bermudagrass show distribution of urine in a sward grazed by mares at a stocking rate of 2.3 head  $\text{ha}^{-1}$ . Photo by Charles Dougherty, University of Kentucky.



steer, increased number of stocking days, and reduced need for stored forage for a system that included a complementary perennial warm-season forage component (Allen et al., 2000).

Animal performance is not always improved by use of complementary forages. In Georgia there was no apparent benefit to using a complementary forage system compared to bermudagrass alone (Brown et al., 2001; Brown and Brown, 2002). Milk production and calf average daily gain in cow-calf production were greater with systems based on bermudagrass than on tall fescue, and intermediate with a complementary forage system that utilized bermudagrass from June to October and tall fescue from November to May.

Factors other than forage species can influence the relative efficiencies of forage systems. Management strategies that influence forage quantity or quality across time can affect animal response within a seasonal-use system. In annual pastures, effects of deferment on animal production were dependent on stocking rate, length of deferment, and initial plant density (Smith and Williams, 1976). In one year of three, time of year was associated with decreased forage intake within heavily and continuously stocked pastures, but not for lighter stocking rates, nor within rotationally stocked pastures (Popp et al., 1997a, 1997b). Even differences among cultivars in distribution of yield and forage quality across the growing season can be sufficient to warrant differing recommendations for season of use (Redfearn et al., 2002).

The relative effectiveness of a given forage for seasonal use depends on the rates and timing of fertilization (Collins and Balasko, 1981a; Vines et al., 2006; Guretzky et al., 2008). Furthermore, fertilization strategies will have a large influence on the input costs of various systems and effects on the environment and ecosystem (Wood et al., Chapter 5, this volume).

The sheer complexity of forage systems makes it difficult to anticipate how overall system efficiency will be affected by management. For example, forage systems that improved average daily gain of stocker cattle also resulted in lower forage production, requiring higher

use of conserved forages (Allen et al., 1992a). Growth and carcass quality responses of cattle on forage-based finishing systems were more responsive to forage fed during the wintering phase than to forage fed during the subsequent finishing phase (Allen et al., 1996). These types of responses cannot be predicted from forage yield and nutritive value studies alone. Well-designed animal performance studies conducted for a sufficient time period are critical for understanding the relationships and real applicability of forage systems to a given region.

### Summary and Recommendations: Season of Grazing and Deferment

In most environments one finds seasons when forage quantity and quality limitations can be mitigated by stockpiling regionally important forages. This is an important prescribed grazing strategy to extend the grazing season, reduce cost of production and improve animal health and performance. Development of year-round complementary forage systems that take advantage of cool- and warm-season species is an important element in achieving desired levels of animal performance and reducing costs. These systems also contribute to ecosystem services that can be achieved by maintaining plant cover and growth in the sward for as much of the year as possible.

### TYPE AND CLASS OF LIVESTOCK

The utilization of pasture to support more than one species of animal has been purported to increase individual animal performance, yield of livestock product per unit land area, and ecosystem stability (Walker, 1994). The focus is on the first two of these assertions.

The conceptual basis underlying the grazing of multiple species on the same land area derives from the competitive exclusion principle (Hardin, 1960), which states that two species cannot both successfully occupy the same ecological niche. Thus, in natural settings, different species of grazing animals occupying the same area will occupy different niches, particularly with respect to their dietary selection behaviors. Differences in ingestive anatomy and grazing behavior among livestock species and their relationship to diet selection were described earlier in the chapter. Because these



Well-designed animal performance studies conducted for a sufficient time period are critical for understanding the relationships”



There is no clear picture emerging: ...sometimes a grazer benefits and sometimes a browser.”

behaviors permit more complete utilization of the existing forage base, it is theoretically possible for a given area to support a greater combined stocking rate of multiple species compared with the stocking rate of either species grazing alone.

In a broad sense, interactions among comingling herbivores can be described as competitive, supplementary, or complementary (Kinyua and Njoka, 2001). These interactions include competition for limited forage resources (competitive relationship), no dietary overlap (supplementary relationship), or the actions of one (or both) benefits the forage quantity or nutritive value for the other (complementary). Other potential mechanisms for interactions exist, including effects on parasite load, or by one animal species utilizing plant species that are potentially toxic to the other. Little research on multispecies grazing is available from pastures of the USA, so the following review is supplemented by research conducted elsewhere.

### Individual Animal Performance

Across a range of stocking rates and sheep:cattle ratios, mixed grazing improved lamb gains by an average of 7% and cattle gains by an average of 11% (Nolan and Connolly, 1989). This occurred in the presence of an average increase in stocking rate of about 2%, indicating the presence of a complementary relationship that benefited both species. In Texas cattle gains were greater when grazing with sheep and goats together than when grazed alone (Taylor, 1985); likewise sheep gains were increased by grazing with cattle and goats, as was percent lamb crop and wool production. However, neither gain nor mohair production of goats was improved by co-grazing with cattle and sheep. Some reports document only minor effects on either species. In a 10-yr study in Utah, cattle gains were slightly depressed (1.01 vs. 1.04 kg d<sup>-1</sup>) when cattle co-grazed with sheep rather than grazing alone, whereas lamb gains were improved slightly (0.25 vs. 0.23 kg d<sup>-1</sup>) when grazing with cattle rather than alone (Olson et al., 1999). In Australia benefits of mixed-species grazing were typically noted for sheep, but not for cattle (Bennett et al., 1970; Hamilton et al., 1976).

The effects on individual animal performance were evaluated from a variety of co-grazing studies (Prins and Fritz, 2008), but the results did not support any broad generalizations. In contrast to ecological theory, which suggests that small grazers outcompete large ones and that large grazers facilitate small ones, they found that “There is no clear picture emerging: sometimes a small species benefits from a large one but sometimes a large one to the detriment of the smaller; sometimes a grazer benefits and sometimes a browser.”

Another mechanism for benefit is reduced parasite loads, particularly in sheep that are co-grazed with cattle (Brelvi, 1979; Bown et al., 1989). A decrease was seen in gastrointestinal helminths and greater weight gains in lambs that had co-grazed with sheep and cattle than in lambs grazing only with sheep (Jordan et al., 1988). In contrast, calves that had co-grazed with sheep had greater gastrointestinal helminth burdens and lower weight gains than those that had grazed only with cattle. In the United Kingdom, sequential grazing with cattle following sheep reduced lamb fecal egg counts, even with regular anthelmintic treatment (Marley et al., 2006).

Greatest growth rates were observed in lambs from mixed-grazing systems, leading to the conclusion that most performance differences were due to factors other than parasite control. Likewise, differences in lamb growth rates with alternate cattle/sheep grazing were due to pasture quality, as no differences were seen in nematode burdens in lambs between alternate grazing vs. sheep-only systems (Moss et al., 1998). Thus, factors other than changes in forage mass and forage quality can mediate effects on animal performance with mixed-grazing systems even though most authors point to forage-mediated effects as the primary drivers.

### Production per Unit Land Area

Although some reports suggest that increases in livestock weight gain per ha are almost assured with co-species grazing, the available literature shows a more complex picture. For example, at a medium stocking rate, mixed-species grazing increased weight gain per ha by 16% above cattle-only grazing (Dickson et al., 1981). Similarly, production per ha was greater with

sheep or mixed-species grazing than with cattle alone (Olson et al., 1999). Conversely, grazing sheep and goats together did not increase productivity per ha, and in a drought year, dramatic weight loss was experienced by sheep grazing with goats, as compared with sheep alone (Wilson and Mulham, 1980).

In a review of the literature, there was no consistent pattern of response of livestock production per ha to co-species grazing (Prins and Fritz, 2008). In six of seven studies reported, gain per ha with combined sheep/cattle grazing was greater than with cattle alone. However, in only one of four studies were combined-species gains greater than gains reported for sheep alone. Further, in only one of three studies did co-grazing goats and cattle result in greater gain per ha than grazing cattle alone. In none of three studies where sheep and goat co-grazing were evaluated was gain per ha improved by co-grazing as opposed to single-species grazing.

Some observers suggest that factors that can influence the competitive balance between forage species can alter the potential influence of co-species grazing on livestock productivity. Drawing general conclusions seems premature, and additional research is required to better understand the biological and ecological mechanisms at play. Though some efforts have been made, much more remains to be done, particularly on temperate pastures in the USA.

Experimental design and appropriate data collection are critical in co- and multispecies grazing studies because of difficulties in determining substitution equivalents between different species. Care must be taken to ensure that any observed increases in gain per ha from combining animal species are not simply a function of increased stocking rate. In other words, the research needs to ensure that a similar increase in gain per ha would not occur simply by addition of animals of the same species.

Substituting one animal species for another based on actual weight is quite common in the existing literature, even though it is generally recognized that animal unit equivalents will be more closely aligned with *metabolic* body weight than with absolute body weight (Allen

et al., 2011). Stocking rates based on actual live weight can be effectively used when dealing with a single species, but utilizing a metabolic body weight-based animal unit becomes critical when dealing with animal species having large variation in individual weights.

### Designing Multispecies Grazing Systems

Strategies have been identified to help quantify degree of dietary overlap (e.g., Abrams, 1980; Squires, 1982), yet it is difficult to establish specific recommendations of animal species, ratios, and numbers based on “degree of dietary overlap” (Scarnecchia, 1985, 1986). Determining these is complex and optimal solutions will differ depending on management goals. In addition, other management factors must be considered such as whether it is desirable to graze different animal species sequentially, rather than simultaneously, in order to allow a greater degree of species-specific management, e.g., mineral supplementation. Such strategies will have different effects on system productivity.

Ultimately models may be developed to allow reasonable prediction of system performance under single- vs. mixed-species grazing strategies (Scarnecchia, 1990). However, at present, we are dependent on empirically established relationships that will necessarily be constrained to specific forages and geographic and climactic conditions. A need exists for research to establish these relationships and

Factors including water sources, shade sources, topography, fencing, salt and feed sources, and season affect the distribution of livestock on pasturelands resulting in unequal distribution of nutrients and varying intensity and frequency of grazing. Photo by Carmen Agouridis, University of Kentucky.





animal production responses to mixed-species grazing are affected by complex interactions among forage, animal, environmental, and management factors”

provide the data necessary for modeling efforts, particularly on pastureland in the USA.

Byington (1985) identified opportunities for increased utilization of multispecies grazing in the eastern USA. These included increased costs associated with forage production, perception by producers of the need for change, availability of technology and knowledge for design and implementation of multispecies grazing systems, and availability of markets for livestock products from such systems. In the 27 yr since Byington documented these factors, the “opportunities” they represent have increased, yet one still finds a lack of robust, systems-oriented research to provide livestock producers with the essential knowledge of how to best implement multispecies grazing practices.

### Summary and Recommendations: Type and Class of Livestock

The direction and magnitude of animal production responses to mixed-species grazing are affected by complex interactions among forage, animal, environmental, and management factors, all of which restrict the ability to predict system performance. Conducting meaningful research in this area is challenging and expensive, but it can be accomplished when careful attention is paid to experimental design to eliminate potentially faulty assumptions, especially as they relate to preconceptions regarding proper species substitution ratios and stocking rates. Ultimately, reasonable prediction of system output will depend on sophisticated modeling efforts that are based on quality field research.

### DISTRIBUTION OF LIVESTOCK IN THE LANDSCAPE

Generally, effects of grazing distribution on animal production are indirect, mediated through alterations in the type and quantity of forage on offer, and possibly through energetic costs associated with foraging behavior, e.g., distance traveled. Because of the large effects of grazing, treading, and manure and urine deposition by herbivores on vegetation structure and botanical composition, a primary effect of manipulating livestock distribution is alteration in the spatiotemporal diversity of pasture forage mass (Rook and Tallwin, 2003) and botanical biodiversity (Ash et al., 2004; Sanderson et al., 2004). Theoretically, productivity should

be maximized when grazing pressure is evenly distributed, yet few data relate the spatial distribution of animals within a pasture with animal performance. Thus, emphasis is often placed at the level of forage production, which is reviewed elsewhere in this chapter.

Some management practices to alter spatial distribution of animals within pastures, e.g., fencing and location of salt or supplemental feed, indirectly affect animal health and performance through controlled access to specific forage types or altering distance traveled. Literature regarding these indirect effects on animal performance is limited. For other strategies, e.g., provision of alternate water sources and adequacy of shade, effects are more direct. Although the literature does allow some generalizations to be made, the data are sufficiently limited to preclude quantitative prediction.

### Fencing and Pasture Size

Subdividing large pastures with fences often increases the uniformity of pasture utilization, although a point exists at which further division presents no additional advantage (Heady and Child, 1999). Little research is at hand to provide quantitative relationships between pasture size and uniformity of use. Grazing distribution and animal performance were evaluated in Wyoming pastures ranging from 24 ha to 207 ha (Hart et al., 1993). The 207-ha pasture was designed to create heterogeneity in grazing utilization, in part by including a maximum distance to water of 5.0 km compared with a maximal 1.6-km distance in the small pastures. Uniformity of pasture utilization was improved, daily distance traveled by cattle was less, and cattle gains were greater in the small, as compared with the large pasture. Unfortunately these effects of pasture size cannot be separated from the effects of distance from water. In an effort to better understand the influence of pasture size, Hacker et al. (1988) evaluated crested wheatgrass pastures ranging from 1 ha to 8 ha in size. No difference was found in overall pasture utilization, uniformity of utilization, or animal weight gain.

### Alternate Water Sources

The importance of providing alternate sources of drinking water, i.e., in addition to existing

natural water bodies, varies depending on levels of total dissolved solids, minerals, microbial contamination, and other water quality factors. Thus, it is difficult to make generalizations on benefits of alternate water sources. Nonetheless, several studies have demonstrated the potential for water source to affect a variety of animal health parameters.

Both cryptosporidia and campylobacter can cause scours in young animals (Merck, 2008) and can be transmitted via drinking water. Starkey et al. (2006) found a 37% increase in cryptosporidium infection in young cattle drinking from springs or streams, as compared with well water. The difference was likely associated with lower levels of fecal contamination in well water. In the United Kingdom, the number of bovine fecal pats within a 5-m radius of a surface water sampling site was positively related to the concentration of *Campylobacter* spp. in the water source (Kemp et al., 2005), suggesting that increased animal presence in and around riparian areas could potentially facilitate spread of disease. Work from the Netherlands indicated that dairy cattle drinking from water sources other than public water supplies (originating either from wells or from streams) had an increased incidence of *Staphylococcus aureus*-mediated mastitis (Schukken et al., 1990, 1991).

A few studies have linked differences in animal growth performance with varying water supply sources. In eastern Oregon, gains by cows and calves were increased across a 42-d grazing period (in each of 2 yr) by providing trace-mineralized salt and water sources away from a stream (Porath et al., 2002). Although part of the response could have been due to provision of trace-mineralized salt, the authors suggest that improvements in performance were likely associated with more uniform grazing distribution in pastures with water sources away from, and other than, the stream. In other research, suckling calves that were provided clean water gained 9% more than those drinking directly from ponds, and yearling heifers provided with clean water gained 20% to 23% more than those drinking pond water (Willms et al., 2002).

Treating “dugout” water by aeration or coagulation/chlorination significantly

reduced *Escherichia coli* load, as well as concentrations of some mineral constituents, and increased dissolved oxygen concentrations (Lardner et al., 2005). Steer gains averaged about 0.1 kg d<sup>-1</sup> greater with treated as compared with untreated water. These responses occurred in the absence of increased parasite load, which, when present, would be expected to increase the benefits of water treatment. Thus, direct benefits to animal health and performance can be derived from providing clean water sources, particularly when levels of bacterial or protozoal contamination are high.

Provision of alternate water sources may not always attract animals away from surface waters. Off-stream water sources served as an attractor for cattle when the temperature-humidity index was moderate, but failed to decrease time spent in riparian zones when the index was high (Franklin et al., 2009). This suggests that when surface waters can contribute to thermoregulation, cattle were less likely to be attracted away from them.

### Shade

Heat stress can adversely affect animal production, primarily by decreasing feed intake (Nienaber et al., 1999; Nienaber and Hahn, 2007). Thermoregulatory behaviors are important in grazing animals since cattle will seek out shade and can increase the time spent under shade without necessarily affecting grazing time (Tucker et al., 2008), although at least one study showed that time spent under shade did reduce grazing time (Coleman et al., 1984). Little information is available directly relating performance of grazing animals to shade provision.

Shade benefited sperm motility and morphology in bulls exposed to warm ambient temperatures (Coleman et al., 1984). In feedlot and free-stall housing studies, shade reduced respiration rates and body temperatures of cattle (Brown-Brandl et al., 2005; Eigenberg et al., 2005; Kendall et al., 2007) and increased average daily gain (Mitlöhner et al., 2002). In Australia shade acted as a protectant from the photosensitization and hyperthermic effects of toxins derived from *Hypericum perforatum* that was orally dosed to sheep (Bourke, 2003). Susceptibility to heat stress of animals



...several studies have demonstrated the potential for water source to affect a variety of animal health parameters.”



...key management factors include minimizing distance to water, providing alternatives to surface water to increase drinking water quality, and providing shade.”

grazing endophyte-infected tall fescue is of great significance to livestock producers in the southeastern USA (Paterson et al., 1995), and this effect may be mitigated partially by shade.

### Summary and Recommendations: Distribution of Livestock in the Landscape

There are few data relating spatial distribution of animals in a pasture with animal performance, but it is likely that distance to water is more important than pasture size with respect to optimizing distribution of grazing and animal performance. Direct benefits to animal health and performance can be derived from providing alternate water sources, but this response is primarily related to water quality and is most likely to occur when levels of bacterial or protozoal contamination are high in existing water sources. Shade is a key factor affecting livestock distribution, and although direct links between shade and improved animal performance are limited, well-documented cases are found of improvement in animal comfort and well-being from shade. Thus, from an animal health and production perspective, key management factors include minimizing distance to water, providing alternatives to surface water to increase drinking water quality, and providing shade.

### PURPOSE 3: IMPROVE OR MAINTAIN SURFACE AND/OR SUBSURFACE WATER QUALITY AND QUANTITY

Nutrients, sediment, and pathogens from pastures must be transported to sensitive locations to affect water quality. Greatest risk of transport is associated with highly permeable soils, severe slopes, insufficient vegetative cover, high water tables, and proximity to streams and wetlands.

#### GRAZING INTENSITY

Similar to forage characteristics and animal performance, the most important grazing management variable associated with ecosystem health of upland and riparian areas is grazing intensity (Van Poollen and Lacey, 1979; cited by Mosely et al., 1999). Challenges to reviewing the literature describing the effects of grazing intensity on water quality and quantity include standardizing the unit of measure for grazing intensity, defining the

period of stocking, and noting the stocking method used (Trimble and Mendel, 1995; Bilotta et al., 2007). Evans (1998) argues for defining grazing intensity in terms of “damage it does to the landscape” rather than in terms of forage characteristics. Others have suggested that grazing intensity be defined based on factors such as hoof impacts and urine and manure deposition and not solely on vegetation consumption (Bilotta et al., 2007).

#### Water Quality

**Nutrients.** In continuously stocked swards in Ohio, nitrate-nitrogen ( $\text{NO}_3\text{-N}$ ), mineral-N, and total P in runoff did not increase with grazing intensity, but organic-N and total organic carbon (C) levels did increase (Owens et al., 1989). In Nebraska the presence of grazing resulted in increased  $\text{NO}_3\text{-N}$  and soluble-P concentrations in runoff and greater chemical oxygen demand (Schepers et al., 1982). Increasing grazing intensity increased levels of ammonium-nitrogen ( $\text{NH}_4\text{-N}$ ),  $\text{NO}_3\text{-N}$ , total P, total organic C, and chemical oxygen demand in runoff. Increased vegetative cover with decreased grazing intensity can reduce nutrient movement into waterways (CAST, 2002). More details on nutrient losses are covered in Chapter 5 (Wood et al., this volume).

**Sediment.** Few studies have examined the effect of grazing intensity on sediment discharge to streams, despite the fact that sediment is a leading cause of impairment in the nation’s streams (EPA, 2009). Increased concentrations of sediment in runoff occurred with increased grazing intensity, and these increases resulted in greater predicted values for  $\text{NH}_4\text{-N}$ , total Kjeldahl N, total organic C, and chemical oxygen demand (Schepers et al., 1982). Three stocking rates (1.5, 2.0, and 3.0 animal units  $\text{ha}^{-1}$ ) were studied in Texas pastures, and the highest stocking rate led to the greatest amount of sediment loss of nearly 1500  $\text{kg ha}^{-1}$  (Warren et al., 1986). In Ohio sediment concentrations in runoff increased with grazing intensity, and these data support the recommendation to exclude livestock from riparian areas (Owens et al., 1989).

**Pathogens.** Although research links the presence of cattle to increased levels of fecal coliforms in streams (Doran and Linn, 1979;

Tiedemann et al., 1987; Howell et al., 1995), studies examining pathogens or pathogen indicator levels in relation to grazing intensity are rare; for pasturelands, none was identified. Increasing stocking rate reduced soil microbial biomass and N mineralization potential (Banerjee et al., 2000). Because grazing intensity can impact soil microbial populations, it is reasonable to expect pathogenic populations would be similarly affected.

### Hydrology

Few studies have investigated the relationship between grazing intensity and water quantity. Most studies have focused on how soil compaction and soil structural properties alter infiltration rates (Bilotta et al., 2007). No study was found that measured direct changes in runoff volume or timing; however, it is expected that such differences exist based on results from infiltration studies. Infiltration studies showed that soil structural changes associated with grazing increased with stocking rate. As stocking rate increases, the animal traffic over any particular area increases and leads to compaction and further breakdown of soil structure and water-stable aggregates. Infiltration rates decreased as grazing intensity increased from “moderate” to “heavy,” but they were not different when the change was from “light” to “moderate” (Gifford and Hawkins, 1978; Usman, 1994; Trimble and Mendel, 1995).

In Texas the heaviest stocking rate produced the lowest infiltration rates for the first 30 min of a simulated storm, but no differences were detected between the light (60% of heavy) and moderate (80% of heavy) stocking rates. After the first 30 min there was no further difference in infiltration rate among stocking rates (Warren et al., 1986). Difficulties in drawing conclusions from the literature regarding the “magnitude of the relationship between soil damage and stocking rate” have been attributed to nonstandardized measurement techniques and parameters, different livestock types, climate, simulated versus natural rainfall, and prior land use differences (Bilotta et al., 2007).

### Stream Morphology

Research into the effects of grazing intensity on the morphology of streams in pasturelands is limited. Seasonal adjustment of stocking rate

based on visual observation of forage mass was recommended as a best management practice to counter streambank erosion in central Kentucky (Agouridis et al., 2005a), particularly during mid- to late summer when forage mass was low and the cooling waters of the stream attracted animals. In New Zealand grazing impacts were greater on smaller streams due largely to their greater accessibility to livestock, since streambanks were closer to water level and water depth was shallower (Williamson et al., 1992). The authors noted that stream morphology was impacted on smaller streams (< 2-m width) when grazing was intensive and the streamside soils were wet.

### Summary and Recommendations: Grazing Intensity

Despite intuitive statements regarding the importance of grazing intensity as a controlling variable in ecosystem health (measured as water quality, water quantity, and riparian and watershed function) (Van Poolen and Lacey, 1979; Mosely et al., 1999), little research has been conducted in this area. Increases in grazing intensity have been linked to increased nutrient, sediment, and fecal coliform loading; streambank erosion; and soil compaction that results in decreased infiltration rates (Table 3.5). Thresholds for grazing intensity, above which substantial environmental impacts occur, have not been established.

A beneficial first step would be to conduct an evaluation of grazing intensity in pasturelands, similar to that done by Trimble and Mendel (1995), to better determine these thresholds. Since research regarding the environmental impacts of grazing intensity is scarce, other grazing studies should be examined to glean relevant information to construct a database for analysis, including those where the focus was on stocking duration and stocking method. In humid areas, of which pasturelands dominate, precipitation is of a much greater magnitude than in many rangelands and, as such, is in excess of infiltration capacity more often than in other climates of the USA (Trimble and Mendel, 1995). As such, the grazing effects on soils, such as reduction in infiltration capacity, will likely exert a significant influence over the hydrograph. Research is needed on effects of grazing intensity on soil characteristics coupled with water infiltration and runoff.



Increases in grazing intensity have been linked to increased nutrient, sediment, and fecal coliform loading; streambank erosion; and soil compaction”



limited research has been conducted to evaluate the effects of rotational vs. continuous stocking on environmental responses”

### STOCKING METHOD

Current grazing management practices are primarily designed to improve forage and animal performance with the overarching goal of increasing profit (Fitch and Adams, 1998; Bellows, 2001). Yet grazing management may also serve as a means to improve environmental responses such as water quality and quantity, riparian health, and watershed function. When riparian areas are grazed, continuous stocking at high grazing intensities has been shown to adversely impact water quality, hydrology, stream morphology, and habitat (Schepers et al., 1982; Kauffman and Krueger, 1984; Belsky et al., 1999; Agouridis et al., 2005a). Rotational stocking may provide environmental benefits, but although a large volume of literature is available that describes forage and animal responses to stocking method, limited research has been conducted to evaluate the effects of rotational vs. continuous stocking on environmental responses. Understanding the potential environmental benefits of alternative stocking management practices will be important in evaluating their overall use and effectiveness.

### Water Quality

**Surface Waters.** Mean total-P in runoff was 34% greater with continuous stocking to maintain a 5-cm height than with rotational stocking leaving a 5-cm post-graze stubble, and 3.7 times greater than rotational stocking leaving a 10-cm post-graze stubble (Haan et al., 2006). The latter did not differ from a non-grazed sward. Percent surface cover by forage was correlated negatively with total-P load in runoff, leading to the conclusion that pasture management should ensure sufficient residual forage mass to reduce the kinetic energy of rainfall. Similarly, a literature review showed that vegetation cover was greater, on average, using rotational than continuous stocking, indicating that a change in stocking method could have long-term implications for water quality (Earl and Jones, 1996). These results do not implicate continuous stocking, in general, as a water quality hazard; instead they indicate that this method in combination with high grazing intensity reduces cover and endangers surface waters. The nearly three-fold lower P in runoff associated with leaving 10- vs. 5-cm of stubble under rotational stocking (Haan et al., 2006) supports the

concept that grazing intensity is the key factor affecting this response.

Kuykendall et al. (1999a) found total Kjeldahl-N, ammonium, total P, and dissolved-reactive-P in surface water was similar for rotational and continuous stocking of pastures receiving broiler litter additions. Results may not apply to pastures not receiving litter.

Winter feeding areas on pastures have been associated with greater runoff, sediment, and P loads as compared with non-use areas leading to research in Ohio to evaluate continuous and rotational stocking methods over winter (Owens et al., 1997; Owens and Shipitalo, 2006). In the continuous method, cattle were fed hay in one pasture during the dormant period (November–April), while in the rotational method, cattle were rotated through pastures to eat stockpiled tall fescue and fed hay. Losses of total-N were 1.9 to 2.5 times greater with the continuous as compared with the rotational method. Organic-N made up over 70% of the N transported in surface runoff from the continuous method. Like Haan et al. (2006) and Earl and Jones (1996), the authors noted less vegetative cover in the continuous than the rotational method (50 vs. ~100%). It should be noted that the rotational overwintering area had more area per cow (i.e., lower stocking rate) than the continuous overwintering area.

**Groundwater.** Nitrogen, particularly  $\text{NO}_3\text{-N}$ , is of concern with regard to groundwater. Rotational stocking of cattle was compared with hay production, both without fertilizer, for groundwater  $\text{NO}_3\text{-N}$  concentrations in Ohio (Owens and Bonta, 2004). Within a 5-yr period, peak groundwater  $\text{NO}_3\text{-N}$  concentrations decreased from levels greater than the EPA standard of  $10 \text{ mg L}^{-1}$  to less than  $5 \text{ mg L}^{-1}$  for both practices. These results suggest that a livestock producer can achieve lower  $\text{NO}_3\text{-N}$  losses and acceptable groundwater  $\text{NO}_3\text{-N}$  concentrations under haying or rotational stocking with low or no N inputs, even in an area with previous high N loading. Based on this and other studies on eastern Ohio watersheds, the authors suggest that N inputs for grazing systems in this region should not exceed  $100 \text{ kg N ha}^{-1}$  annually to maintain groundwater  $\text{NO}_3\text{-N}$  concentrations

**TABLE 3.5.** Water quality, hydrology, and streambank morphology responses to grazing intensity.

Response <sup>1</sup>	Response to increased grazing intensity	Stocking rate <sup>2</sup>	Reference
NO <sub>3</sub> -N, mineral-N, total P	No change	No livestock, 17 cows (26 ha) <sup>-1</sup> summer only grazing, 17 cows (26 ha) <sup>-1</sup> year-round grazing	Owens et al., 1989
Organic-N, TOC, sediment	Increased	No livestock, 17 cows (26 ha) <sup>-1</sup> summer only grazing, 17 cows (26 ha) <sup>-1</sup> year-round grazing	Owens et al., 1989
NO <sub>3</sub> -N	Increased	60% available forage utilization, 80% available forage utilization, and 80% available forage utilization with grain supplement (33% dry matter intake)	Stout et al., 2000
NO <sub>3</sub> -N, NH <sub>4</sub> -N, total P, soluble P, COD, TOC, sediment	Increased	No livestock, 35–40 cow-calf pairs (40 ha) <sup>-1</sup>	Schepers et al., 1982
Sediment loss	Increased	0.68, 0.51, and 0.32 ha AU <sup>-1</sup>	Warren et al., 1986
Soil microbial biomass, N mineralization potential	Decreased	2.2 and 1.1 steers ha <sup>-1</sup>	Banerjee et al., 2000
Infiltration rates	Decreased	0.65, 1.2, and 2.5 AUM ha <sup>-1</sup>	Trimble and Mendel, 1995
Infiltration rates	Decreased	0.34, 0.68, and 0.51 ha AU <sup>-1</sup>	Warren et al., 1986
Streambank erosion	Increased	0 to 1600 kg ha <sup>-1</sup>	Agouridis et al., 2005a

<sup>1</sup>TOC indicates total organic C; COD, chemical oxygen demand. <sup>2</sup>AU indicates animal unit; AUM, animal unit months.

below 10 mg L<sup>-1</sup>, though this annual rate of N may be too high to allow lowering of existing high NO<sub>3</sub>-N levels in groundwater. Rates are regionally specific, as 200 kg N ha<sup>-1</sup> yr<sup>-1</sup> did not affect soil profile NO<sub>3</sub>-N water quality in bermudagrass pastures or hay fields in Georgia (Franzluebbbers and Stuedemann, 2003b). Further, NO<sub>3</sub>-N leaching from bermudagrass hay fields was minimal when N was applied at < 90 kg N ha<sup>-1</sup> growth period<sup>-1</sup> (typically 3–4 growth periods yr<sup>-1</sup>) in Florida (Woodard and Sollenberger, 2011).

The effects of summer and winter rotational stocking practices on NO<sub>3</sub>-N and dissolved reactive-P were also studied (Owens et al., 2008). Groundwater discharge from small watersheds affected the flow and water quality from larger watersheds. It was estimated that 50% of the NO<sub>3</sub>-N loads and 30% of the dissolved reactive-P loads in the stream flow originated from groundwater. Examination of water quality trends prior to cessation of fertilizer application indicated that it would likely take several years for the effects of a change in grazing management to become measurable in terms of water quality. In karst terrain, subsurface drainage and nutrient

transport to groundwater can be rapid. Several years may be required before past land uses are no longer influential, particularly with respect to soil nutrient concentrations (Zaimes et al., 2008a).

**Sediment.** Sediment loss from pastures can be influenced by ground cover, sward height, treading damage, surface slope, and soil moisture (Haan et al., 2006). Sediment loss from a continuously stocked sward maintained at a height of 5 cm was nearly twice that from a rotationally stocked treatment with a 5-cm post-graze sward height (Haan et al., 2006) because of greater average cover for rotational than continuous stocking. Maintaining good vegetative cover limited soil loss from pastureland in Ohio where cattle were overwintered (Owens et al., 1982; Owens et al., 1983b; Owens and Shipitalo, 2009). Changing management on an area from rotational stocking in summer plus continuous overwinter stocking to summer-only rotational stocking reduced annual soil loss from 2.3 to 0.15 Mg ha<sup>-1</sup> (Owens et al., 1997). Sovell et al. (2000) compared rotationally and continuously stocked pastures in southeastern Minnesota and found that streams in continuously stocked



modifications to cattle management could reduce fecal coliform levels in shallow groundwater.”

pastures had higher turbidity levels than those in rotationally stocked sites.

**Pathogens.** Few studies have examined the effect of stocking method on pathogenic organism levels either in surface water or in groundwater. Fecal coliform levels in Minnesota streams were greater within continuously than rotationally stocked pastures (Sovell et al., 2000). Although research on bacterial movement from pastures usually focuses on surface runoff, studies in karst terrain show surface water can rapidly move into springs and wells. In central Kentucky, fecal bacteria populations frequently exceeded primary contact standards at all sites sampled (Howell et al., 1995). Fewer samples exceeded primary contact standards from pastures that were intensively grazed and then rested than from pastures stocked continuously. Therefore, modifications to cattle management could reduce fecal coliform levels in shallow groundwater. In West Virginia, successful forage management practices allowed for increased stocking rate, but also led to increased levels of fecal bacteria in groundwater (Boyer, 2005).

### Hydrology

Hydrograph shape is influenced by variables including soil compaction, upland and riparian vegetation, and stream morphology; all that can be influenced by grazing activity (Kauffman and Krueger, 1984; Agouridis et al., 2005a). However, few studies have examined effects of different stocking methods on hydrology. Although not statistically significant, Haan et al. (2006) showed that water infiltration rates ranked in order of rotationally stocked to a 10-cm stubble height (67 mm h<sup>-1</sup>), non-grazed (62 mm h<sup>-1</sup>), rotationally stocked to a 5-cm stubble height (57 mm h<sup>-1</sup>), and continuously stocked (55 mm h<sup>-1</sup>). Subsequently, percentage of rainfall that became runoff was similar from non-grazed (6.4%) and rotationally stocked to 10-cm stubble height treatment (12.7%), but both had less runoff than did rotationally stocked to a 5-cm height (20.7%) and continuously stocked treatments (21.9%).

In a multiyear study in eastern Ohio, a small watershed was rotationally stocked in the summer and used continuously as a wintering paddock (Owens et al., 1997).

Runoff during both the summer and winter was higher than from an adjacent watershed that was stocked rotationally in summer only. Reduced vegetative cover during winter was an important factor causing increased runoff. Monthly runoff was greater with continuous than rotational stocking 75% of the time (Owens and Shipitalo, 2009). In Georgia, however, no difference was seen in annual surface runoff volume between pastures treated with broiler litter that were continuously or rotationally stocked year-round (Kuykendall et al., 1999a).

### Stream Morphology

Numerous studies have shown that uncontrolled livestock grazing can negatively impact stream morphology (Kauffman and Krueger, 1984; Trimble, 1994; Owens et al., 1996; Agouridis et al., 2005b). In Iowa continuous, rotational, and intensive rotational (six or more paddocks, 1- to 7-d grazing period, 30- to 45-d rest period) stocking were compared (Zaimes et al., 2008b). Streambank erosion rates were not different among the treatments, but the intensive rotational treatment had a lower percentage of severely eroding streambanks than the other grazing treatments. Pastures with exclusion fencing had streambank erosion rates of 22 mm yr<sup>-1</sup>, while rates were 101 to 171 mm yr<sup>-1</sup> for continuous stocking, 104 to 122 mm yr<sup>-1</sup> for rotational stocking, and 94 to 170 mm yr<sup>-1</sup> for intensive rotational stocking. Thus grazing increased streambank erosion.

In Minnesota a higher percentage of suspended sediment occurred in the stream, and a higher percentage of exposed streambank soil was found for continuously compared with rotationally stocked sites (Sovell et al., 2000). In Wisconsin, Lyons et al. (2000) measured lower amounts of streambank erosion and suspended sediment in the stream where intensive rotational stocking was practiced, compared with continuous stocking. They concluded that intensive rotational stocking could be substituted for development of riparian buffer strips when only streambank erosion and suspended sediment were considered. Similar conclusions were made in Minnesota if the grazed sites were managed in an environmentally sustainable manner (Magner et al., 2008). It is unlikely

that riparian benefits from changing from continuous to rotational stocking will be realized unless sufficient time is allocated for streambanks to recover and for establishment of riparian vegetation, particularly woody species (Fitch and Adams, 1998).

### Summary and Recommendations: Stocking Method

The majority of a small number of studies indicate that rotational stocking is less detrimental to water quality, hydrology, and stream morphology than is continuous stocking (Table 3.6). A few studies indicated reduced ground cover from grazing can lead to increased runoff and lower quality of surface waters from grazed pastures. Accumulation of additional forage mass and ground cover during regrowth periods accounts for some of the benefits attributed to rotational stocking. However, additional research is needed to fill knowledge gaps, specifically on effects of vegetation characteristics (e.g., types, height, percent cover) on water quality and hydrology, on impact of grazing methods in karst areas and how to reduce such impacts (e.g., sinkhole protection), and the effects of stocking methods on reducing transfer of pathogenic organisms to waterways.

The literature suggests a role for rotational stocking in protecting water quantity and quality. The choice of continuous or rotational stocking, however, is likely to be less important from an environmental perspective than ensuring that an appropriate stocking rate is maintained, season and duration of grazing in riparian areas are controlled, or even excluded depending on site conditions, and a sufficient riparian buffer is established and maintained to enhance water quality, streambank stability, and in-stream and riparian habitat.

### SEASON OF GRAZING AND DEFERMENT

Pasturelands in the USA are largely located in humid regions in which annual precipitation amounts exceed annual evapotranspiration (Trimble and Mendel, 1995), resulting in periods of high runoff (Di and Cameron, 2002). A large portion of US pasturelands receive more than 1000 mm of rainfall annually (NOAA, 2005) with spring months typically the wettest and late summer to early

autumn months the driest. Periods of high soil saturation coupled with seasonal changes in water requirements of pasture species affect runoff or drainage volumes and constituent (e.g., N) transport rates (Owens et al., 1983a; Stout et al., 1998; Di and Cameron, 2002; Owens et al., 2003) as well as streambank stability (Scrimgeour and Kendall, 2002). Furthermore, the large presence of karst topography in pasturelands (Veni, 2002) may have management-specific implications with regards to water quality. Research is limited on environmental effects due to season and grazing deferment practices, particularly in light of the climatic and geologic characteristics associated with pasturelands. Such knowledge is vital to develop management strategies that minimize factors such as  $\text{NO}_3\text{-N}$  leaching and enhance benefits such as biodiversity in pasturelands.

### Water Quality

**Nutrients.** Season of grazing and deferment have significant effects on  $\text{NO}_3\text{-N}$  leaching due to 1) accumulation of  $\text{NO}_3\text{-N}$  in the soil coupled with high runoff or drainage, 2) seasonal demands of plants, and 3) high levels and nonuniform waste dispersal of N by grazing livestock (Di and Cameron, 2002). For example, 60% to 90% of the N ingested by a cow is returned to the pasture, largely via urine, and is nonuniformly distributed (Haynes and Williams, 1993). These “patches” contain N levels well in excess of plant needs, thereby creating potential for  $\text{NO}_3\text{-N}$  leaching when excess precipitation occurs.

Timing grazing to coincide with increased nutrient demands from forage is one method to reduce the transport of excessive nutrients to surface and/or ground waters. Stout et al. (1997) examined  $\text{NO}_3\text{-N}$  losses from seasonal urine deposits on cool-season pastures in Pennsylvania. Loss increased during the year from 18% of that deposited in spring to 28% in summer and 31% in autumn. Soil type caused differences in that Hartleton Channery silt loam lost 41% to 56% of the  $\text{NO}_3\text{-N}$ , while Hagerstown silt loam lost only 16% to 19% (Stout et al., 1998). Part of the difference was attributed to increased plant growth and more N uptake on the Hagerstown soil. Based on these studies, Stout et al. (1997, 1998) point to the need to manage grazing to minimize  $\text{NO}_3\text{-N}$  leaching particularly in autumn when



The literature suggests a role for rotational stocking in protecting water quantity and quality.”



In July 40% of the urine-N was recovered by plants, but in November recovery was negligible.”

plant growth slows and through the later winter and early spring before growth resumes.

Similarly,  $\text{NO}_3\text{-N}$  levels were greater in subsurface flows from winter grazing and feeding areas as compared with summer-grazed areas in Ohio (Owens et al., 1983c). Plant uptake of urine-N declined linearly and soil levels increased linearly due to monthly urine-N applications between July and November (Cuttle and Bourne, 1993). In July 40% of the urine-N was recovered by plants, but in November recovery was negligible. Similarly, only 3% of the urine-N was found in the soil in July compared with 66% in November. This accumulated N was lost over the winter. When  $^{15}\text{N}$ -labeled urine was applied to plots during May through October, the largest N losses occurred with late-season application due to decreases in N utilization rate by plants (Decau et al., 2003). Over a 2-yr period, small seasonal increases were seen in total-N and  $\text{NO}_2^- + \text{NO}_3^-$  levels in a monitored stream due to early-season and late-season grazing compared with no grazing. There were higher levels of total P in the stream with all-season grazing compared with the other treatments (Scrimgeour and Kendall, 2002).

**Sediment.** Few studies have examined the effect of season and grazing deferment on sediment production and loss. In Ohio over 60% of sediment loss from grazed pasture occurred during November through April (Owens et al., 1997). Greatest losses occurred during March through June, and the smallest losses occurred from August through October. Estimated annual sediment losses were  $2.3 \text{ Mg ha}^{-1}$  when summer rotational stocking was combined with winter stocking and feeding on the same area,  $0.15 \text{ Mg ha}^{-1}$  with only summer rotational stocking, and  $< 0.1 \text{ Mg ha}^{-1}$  with no grazing. McDowell et al. (2005) examined the effects of unrestricted grazing, grazing restricted to 3 h, and no grazing during wintering of dairy cattle. Sediment loads in runoff were six times greater with unrestricted grazing and two times greater from restricted grazing as compared with no grazing.

**Pathogens.** Since bacteria of fecal origin are mesophilic, it is expected that season and grazing deferment would impact populations. Numbers of *E. coli* in streams associated with

grazing and forestry land uses were greater during the warmer summer and autumn months than in winter and spring (Donnison et al., 2004). A similar trend occurred with fecal coliforms in sheep-grazed pastures in England (Hunter et al., 1999). Similarly, when pastures in the karst region of West Virginia were grazed during spring and summer, the fecal coliform levels in resurgent groundwater peaked in the summer, declined in autumn, and returned to pre-grazing levels during winter (Pasquarell and Boyer, 1995). With grazing deferment in Australia, McDowell et al. (2005) noted that *E. coli* levels in overland flow increased with unrestricted winter grazing by dairy cattle but not for grazing restricted to  $3 \text{ h d}^{-1}$ .

### Hydrology

Although seasonal variation in precipitation, plant growth, and hence runoff and drainage occurs in pasturelands (Di and Cameron, 2002; NOAA, 2005), little research has examined the effects of season and grazing deferment on surface and subsurface hydrology. In Ohio pastures,  $\geq 50\%$  of the November through April precipitation was routed to subsurface flow, but it was  $\leq 20\%$  of that during May through October (Owens et al., 2003). This was mainly due to reduced evapotranspiration during the November through April dormant season. This changed water quality; greatest loss of nutrients occurred during the dormant season with surface waters largely transporting P, K, and total organic-C, while subsurface waters transported N, Ca, Mg, Na, and Cl (Owens et al., 1983b).

### Stream Morphology

Excluding livestock completely from riparian areas improved streambank stability (Trimble, 1994; Owens et al., 1996; Zaimes et al., 2008a), but few reports have examined the potential of limited grazing on morphological parameters. Scrimgeour and Kendall (2002, 2003) noted a 50% increase in bank stability and three to five times more vegetation when livestock were excluded from riparian areas as compared with allowing early- or late-season grazing. They concluded that use of deferred grazing was not likely to produce more stable banks or greater riparian vegetation.

Streambanks did not recover during the off-season from the erosive effects of grazing

**TABLE 3.6.** Water quality, hydrology, and streambank morphology responses to stocking method.

Response <sup>1</sup>	Comparison <sup>2</sup>	Difference	Note	Reference
TP and sediment loss	C > R > N	TP: C was 1.3 times greater than R (5 cm); R (5 cm) was 2.8 times greater than N; C was 3.7 times greater than N	Percent ground cover was directly correlated to TP and sediment loss	Haan et al., 2006
		Sediment loss: C was 2 times greater than R		
TKN, NH <sub>4</sub> , TKP, DRP, runoff	C = R	Not significant at $P \geq 0.10$	Pastures were subjected to broiler litter applications	Kuykendall et al., 1999a
TN, runoff volume	C > R	TN: C was 1.9–2.5 times greater than R	TN: Ground cover was less than 50% for C and about 100% for R	Owens and Shipitalo, 2009
		Runoff: C greater than R 75% of time	Runoff: Amount of winter vegetative cover indirectly correlated to runoff volumes	
FC	C > R	C was over 2 times greater than R for stream mean values	FC levels still exceeded water quality standards	Howell et al., 1995
Annual soil loss	C > R	C was 15.5 times greater than R	Increased runoff with C, attributed to increased soil compaction and decreased vegetation	Owens et al., 1997
Streambank erosion	C, R > N	C and R were 2–5 times greater than N	Consideration should also be given to constituents such as P in streambanks	Zaimes et al., 2008a
Turbidity, FC, fines, exposed streambanks	C > R	Turbidity: C was about 1.5 times greater than R;	Turbidity strongly correlated with TSS for studied streams	Sovell et al., 2000
		FC: C was about 2 times greater than R;		
		Exposed streambanks: C was about 9 times greater than R		
Fines (embeddedness), streambank erodability	C > R	Fines (embeddedness): C was about 2 times greater than R;	Streambank erosion significant source of sediment to streams	Lyons et al., 2000; Weigel et al., 2000
		Streambank erodability: C was about 1.5 times greater than R		

<sup>1</sup>TP indicates total P; TKN, total Kjeldahl N; TKP, total Kjeldahl P; FC, fecal coliforms; TOC, total organic C; and COD, chemical oxygen demand. <sup>2</sup>C indicates continuous stocking; R, rotational stocking; N, non-grazed.

(Agouridis et al., 2005b), suggesting other factors such as prior land use, soil types, and geology should be carefully examined before season of grazing deferment is discounted as a streambank management strategy. Since soil strength is decreased under saturated conditions, Bellows (2001) recommended that grazing of riparian areas be permitted only after streambanks “dried out.”

### Summary and Recommendations: Season of Grazing and Deferment

The largest effects of grazing on water quality typically occurred during the dormant season (i.e., fall/winter months), particularly

NO<sub>3</sub>-N leaching and sediment loss. However, the highest levels of fecal organisms were often found in water during the summer months when temperatures were warmest (Table 3.7). Similarly for hydrology, greater runoff rates occurred during the dormant season when evapotranspiration was lowest. Research on grazing management impacts on streambanks is limited, but results suggest that removal of livestock from riparian areas during periods of high soil saturation is warranted.

Winter feeding on pasture significantly alters water quality and hydrology, but more research

**TABLE 3.7.** Water quality, hydrology, and streambank morphology responses to season.

Parameter	Comparison <sup>1</sup>	Difference	Note	Reference
NO <sub>3</sub> -N	A > Su > Sp	18% loss in Sp, 28% in Su, 31% in A	Differences attributed to plant uptake	Stout et al., 1997
NO <sub>3</sub> -N	W > Su	W nearly twice Su	Subsurface flows	Owens et al., 1983c
Urine-N	Plant uptake: Su > A	Plant uptake: 40% in Su, negligible in A;	Linear decline in plant uptake and linear increase in soil levels	Cuttle and Bourne, 1993
	Soil levels: A > Su	Soil levels: 3% in Su, 66% in A		
<sup>15</sup> N-labeled urine	Plant uptake: Sp > A	Average plant uptake: 62% Sp, 17% A	Uptake by plants varied with soil type	Decau et al., 2003
Sediment	Late A, W, and early Sp > late Sp, S, and early A	Accounted for over 60% of loss	Greater losses during dormant season	Owens et al., 1997
Escherichia coli	Su and A > Sp and W	2–3 log difference	Attributed to warmer temperatures	Donnison et al., 2004
Fecal coliforms	Su > A; recovery in W	August peak with decline until November	Seasonal variation related to presence/absence of cattle, amount of soil water present, bacterial storage in soil, and bacterial die-off rates	Pasquarell and Boyer, 1995
Subsurface flow	Late A, W, and early Sp > late Sp, S, and early A	Late A, W, and early Sp (dormant season): over 50% from precipitation;	Greater amounts of precipitation becoming subsurface flow during dormant season	Owens et al., 2003
		Late Sp, S, and early A (growing season): 20% or less from precipitation		

<sup>1</sup>Sp indicates spring (March–May); Su, summer (June–August); A, autumn (September–November); and W, winter (December–February).

is needed to develop management strategies to minimize effects on surface and subsurface waters. Excluding grazing livestock from riparian areas during sensitive time periods, e.g., when evapotranspiration levels are at their lowest, is a good option, while cattle still graze and can be fed hay on nonriparian pastures during the dormant period. Best management practices need to be developed for these winter feeding areas to minimize environmental impacts.

Importantly, complete livestock exclusion from portions of pasturelands, such as riparian areas, may not be the best solution for the ecosystem. Some level of vegetation disturbance is likely needed to maintain or improve biodiversity on pasturelands (Connell, 1978). However, questions remain as to the level and timing of such disturbances and what biodiversity component is the benefactor. Such knowledge will allow for improved management of

pasturelands and their riparian areas to support livestock production and increase diversity of desired plant, mammalian, avian, and benthic species.

### TYPE AND CLASS OF LIVESTOCK

A large body of literature describes the environmental impact of beef cattle on grazing lands, particularly with regard to grazing management and livestock distribution (Clark, 1998; Belsky et al., 1999; Agouridis et al., 2005a), but little is available for dairy cattle, horses, sheep, or goats. A review of the literature revealed a notable lack of research in many areas related to environmental impact due to livestock type. Most available research focused on effects of pathogenic organisms on water quality.

### Animal Size

Larger animals exert more pressure on the soil than smaller animals, leading to altered soil

structure (Bilotta et al., 2007), which, in turn, affects both hydrology and erosion processes on pastures and along streambanks (Trimble and Mendel, 1995; Belsky et al., 1999; Agouridis et al., 2005a). The differing types of livestock also produce differing amounts of urine and manure, which vary in microbial content and nutrient concentration. Thus, it is expected that animals of different sizes will have different effects on water and the environment (ASABE, 2005; Weaver et al., 2005).

### Grazing Characteristics

Preferred location of grazing, biting mechanisms, and amount of forage consumed daily vary among types of livestock. Cattle typically prefer to forage in riparian areas and avoid steep slopes (Marlow and Pognacnik, 1986; Evans, 1998; USDA-NRCS, 2003), whereas sheep graze predominately in the uplands (Platts, 1981; Arnold, 1984; Glimp and Swanson, 1994). Cattle also tend to damage the riparian environment to a greater extent than horses (Trimble and Mendel, 1995; Menard et al., 2002).

## SURFACE WATER QUALITY

**Streambank Erosion.** Different types of livestock may alter streambanks or riparian areas differently due to grazing preferences. For example, cattle-grazed pastures had significantly more streambank erosion than horse-grazed pastures (Zaimes et al., 2006). Sheep prefer to graze uplands but will graze riparian areas if stocked at high rates (Platts, 1981). At high stocking rates, sheep grazing riparian areas led to increased stream width by four-fold and reduced mean depth to 20% of previous levels. This change in channel morphology resulted in increased water temperature.

**Pathogenic Organisms.** Livestock producers often allow access to open water bodies such as streams and ponds as a source of drinking water, resulting in an increased level of activity along the water's edge. Manure may contain pathogenic organisms such as *Cryptosporidium* spp., *Giardia* spp., or *E. coli*, which can be carried by runoff into nearby surface waters, and even infiltrate to ground waters during rainfall events (Niemi and Niemi, 1991). Furthermore, these pathogens that enter surface waters may be resuspended by the higher

stream flows produced during runoff-producing rainfall events (Stephenson and Rychert, 1982).

Livestock wastes serve as a source of both *Giardia* and *Cryptosporidium* on pastures. *Giardia* was found in 38% of sheep, 29% of cattle, and 20% of the horse waste sampled (Olson et al., 1997). *Cryptosporidium* was found in 23% of pastured sheep, 20% of pastured cattle, 17% of pastured horses, 50% of manure from beef cattle feedlot pens, and 68% of the manure from dairies (Anderson, 1991, 1998). Dairies in the eastern USA had a higher percentage of positive samples than those in the western USA, perhaps due to greater pasture use and higher rainfall in the East resulting in billions of oocysts being washed into surface waters. A “hydrologic connection” was proposed as the primary means for transfer of organisms to the water from land deposits of the manure (Atwill et al., 1999). Overland flow accounted for 99.8% of oocyst transport, and only 0.2% was attributed to subsurface flow.

Animal manure is a major source of *E. coli* O157:H7, which has been isolated both in depositions and in rectal samples from cattle, sheep, horses, and wildlife (Wang et al., 1996; Renter et al., 2004). *E. coli* O157:H7 was detected in 16% of rectally retrieved manure samples in the United Kingdom and 1.9% to 5% in the USA (Sargeant et al., 2000; Oliver et al., 2005). Bovine manure, especially from dairy cattle, contains the highest concentration of *E. coli* O157:H7 among livestock (Wang et al., 1996). Since most enteric organisms are capable of fermenting lactose, lactating cows provide an optimal environment for the organism. *E. coli* O157:H7 was four times more prevalent in deposits of fresh manure from calves than adult cattle (Renter et al., 2004). Drinking water is thought to be a major contributor to the re-inoculation and subsequent excretion of *E. coli* O157:H7 in adult cattle (Wang et al., 1996).

**Nutrients.** Concentrations of nutrients are related to the type of manure and urine excreted (e.g., animal type) and with the volume (e.g., animal size). In dairy pastures in central Pennsylvania, as the amount of urine applied increased, the volume of urine leached increased, indicating that larger livestock are



Livestock wastes serve as a source of both *Giardia* and *Cryptosporidium* on pastures.”



As cattle frequent an area, they remove vegetation, concentrate waste, and may compact the soil, providing ideal conditions for runoff contributions to waterways”

TABLE 3.8. Range of pathogens sizes in comparison to soil particles sizes.

Soil particle size <sup>1</sup>		Pathogen class <sup>2</sup>		
Classification	Diameter (µm)	Classification	Diameter (µm)	Examples
Sand	50–2000	Protozoa	5–1000	<i>Cryptosporidium</i> and <i>Giardia</i>
Silt	2–50	Bacteria	0.5–6	<i>Escherichia coli</i>
Clay	< 2	Viruses	0.02–0.75	Rotavirus and enterovirus

<sup>1</sup>USDA Textural Classification (McCuen, 2005). <sup>2</sup>Adapted from Oliver et al. (2005).

likely associated with greater NO<sub>3</sub>-N leaching from pastures (Stout, 2003).

Groundwater Quality

*Pathogenic Organisms.* The depth to which pathogens can travel depends on both the organism’s dimensions and the soil matrix (Table 3.8) (Oliver et al., 2005). Protozoa such as *Cryptosporidium* spp. and *Giardia* spp., which typically range in diameter from 3 µm to 1 mm, can pass through sand and coarse silt particles, but face greater difficulty traveling through a soil matrix comprised largely of clay particles. Hence, soils comprised largely of clay with low bulk density are more effective at removing protozoa, and likely bacteria, than are high bulk density, sandy soils (Atwill et al., 2002).

*Nutrients.* Dairy cattle on pasture caused a 60% to 70% increase in the NO<sub>3</sub>-N load to a cave stream in southwestern West Virginia (Boyer and Pasquarell, 1996). Concentrations of NO<sub>3</sub>-N were also high in an area where beef cattle congregated for shade and water. These results indicate that groundwater contamination is particularly a concern in karst terrain where downward flow readily occurs.

Summary and Recommendations: Type and Class of Livestock

Although pasturelands support a sizeable percentage of the cattle, horses, sheep, and goats in humid areas of the USA, little research has been done to assess their relative influence on water quality, hydrology, riparian health, and watershed function. Most of the research has been conducted with beef cattle and particularly on effects of livestock distribution. Few studies have assessed the effects of livestock type and age on water quality, hydrology, riparian health, and watershed function. From the comparative studies conducted, results suggest that 1) young calves are a greater source of pathogens such as *Cryptosporidium*, *Giardia*,

and *E. coli* O157:H7 than adult cattle; 2) dairy cattle have a higher presence of such pathogens than other livestock; and 3) dairy cattle make a greater contribution to N and pathogen loading of waterways than other livestock.

Research is needed to better assess the effects of animal size, manure characteristics, and microbial differences on the environment. In particular, lacking is research on effects of horses and sheep. The carrying capacity of a pasture needs to be thought of in new terms, not just forage based but also environment based (Evans, 1998). By better understanding the effects of different types of livestock at different ages on the environment, the negative effects can be mitigated by developing best management practices such as riparian buffers and refining grazing methods to prevent problems such as overgrazing.

LIVESTOCK DISTRIBUTION IN THE LANDSCAPE

Water sources, shade sources, topography, fencing, salt and feed sources, and season affect the distribution of livestock on pasturelands. This results in unequal distribution of nutrients, bacteria, and other contaminants in the pasture (Agouridis et al., 2005b). As cattle frequent an area, they remove vegetation, concentrate waste, and may compact the soil, providing ideal conditions for runoff contributions to waterways, hence influencing water quality and quantity as well as riparian and watershed function (CAST, 2002). Luring cattle away from riparian areas is an important goal of prescribed grazing and can decrease nutrient, bacteria, sediment, and other pollutant loads to waterways.

Much research has been conducted in western USA rangelands, where researchers have noted that livestock grazing alters watershed hydrology, stream morphology, soil structure,

water quality, and riparian habitat (Belsky et al., 1999; Agouridis et al., 2005a). Knowledge gained from rangeland studies is helpful; however, the transferability of the results to pasturelands in the eastern USA is uncertain because plant species and precipitation magnitude and intensity are markedly different (Hershfield, 1961; Trimble and Mendel, 1995). Responses of watersheds, stream systems, and associated riparian areas to grazing are not universal (Juracek and Fitzpatrick, 2003), even among pasturelands in the eastern USA, and thus prescribed grazing practices are not immediately transferable and cannot be expected to elicit similar responses for a range of ecosystems (Sarr, 2002). An understanding of local riparian systems and the functions they perform is a necessary step in managing livestock grazing (Fitch and Adams, 1998).

This section addresses management interventions designed to alter livestock distribution in the landscape, with the goal of achieving production while maintaining or improving water quantity and quality. These interventions include providing alternate water and shade sources and use of exclusion fencing and riparian buffers.

### Alternate Water Sources

Few studies have examined the ability of alternate water sources (e.g., water trough) to affect grazing distribution patterns on pasturelands, and thus affect water quality, hydrology, morphology, or habitat. Among existing studies, results are mixed with regard to the effectiveness of alternate water sources. For example, installation of a water trough in Virginia reduced amount of time cattle spent in the stream by 89% and in the riparian area by 51% (Sheffield et al., 1997). In Georgia, even when the area of nonriparian shade was small, a water trough reduced the amount of time cattle spent in the riparian area (Byers et al., 2005). Conversely, research in North Carolina and Alabama showed no change in time cattle spent in riparian areas following trough installation (Line et al., 2000; Zuo and Miller-Goodman, 2004) or that a trough did not eliminate continued use of riparian areas for lounging (James et al., 2007). Ambient temperature and the degree to which livestock rely on the riparian area for cooling may contribute to these different findings. During the warm

season in humid environments, livestock increase use of riparian areas for cooling during midday and the afternoon (Zuo and Miller-Goodman, 2004). Additionally, livestock age may be important, as older cows seek heat relief by frequenting streams rather than drinking water from a trough (Line et al., 2000).

**Water Quality.** Installing a water trough in the pasture improved water quality in three Virginia streams (Sheffield et al., 1997). Cattle spent 89% less time drinking from the streams, resulting in reductions in total suspended solids (90%), total N (54%), total P (81%), sediment-bound P (75%), fecal coliforms (51%), and fecal streptococci (71%). Having water troughs available reduced median base flow loads for dissolved reactive P by 85%, total P by 57%, total suspended solids by 95%, and *E. coli* by 95% (Byers et al., 2005). Conversely, no significant water quality improvement accrued from use of an alternate water source in one study in North Carolina (Line et al., 2000).

**Stream Morphology.** Use of an alternate water source did not reduce streambank erosion in a riparian area grazed by cattle in Kentucky (Agouridis et al., 2005b). In contrast, a 77% reduction in streambank loss was observed after installing a water trough in Virginia (Sheffield et al., 1997). The difference in results may be due to varying weather conditions, stream characteristics, and/or stocking rates, which differed among experiments.

### Shade Sources

Shading, both natural and artificial, reduced the heat load to cattle by 1400 kJ h<sup>-1</sup> (Ittner et al., 1951) and can be an effective modifier of livestock distribution. In warm weather, livestock spend a disproportionate amount of time in shade (Dubeux et al., 2009), and areas around shade were a more powerful draw to livestock than areas around water troughs (Mathews et al., 1999). Addition of artificial shade in the greater pasture did not alter time cattle spent in riparian areas containing large trees (Zuo and Miller-Goodman, 2004). They concluded that if natural shade was accessible, cattle would not use artificial shade either alone or in combination with an alternate water source. In Georgia establishment of nonriparian shade is advocated as a means of



if natural shade was accessible, cattle would not use artificial shade either alone or in combination with an alternate water source.”



Unrestricted grazing of cattle has been linked to water quality impairments, streambank erosion, and in-stream habitat alterations in pasturelands.”

luring cattle away from riparian areas (Byers et al., 2005). No study was found that evaluated effects of alternate shade sources on water quality and hydrologic, morphologic, and biotic responses.

### Exclusion Fencing

Several studies have examined either the effects of unrestricted grazing on riparian ecosystems and water quality or on the effectiveness of exclusion fencing to mitigate grazing effects on riparian areas. Unrestricted grazing of cattle has been linked to water quality impairments, streambank erosion, and in-stream habitat alterations in pasturelands. Relative to exclusion, unrestricted cattle access resulted in a four-fold increase in total Kjeldahl N, five-fold increase in total P, four-fold increase in ammonium, 11-fold increase in total suspended solids, 13-fold increase in turbidity, and 36-fold increase in *E. coli* in stream water (Vidon et al., 2008). Increases in loads of dissolved reactive-P, total P, and total suspended solids were found during storm events and when cattle were permitted free access to the stream; the latter also increased *E. coli* load (Byers et al., 2005).

Streams with riparian grazing had greater amounts of eroding banks, greater percentages of suspended sediment, greater water temperatures, larger reductions in invertebrate food sources, and lower density of macrobenthos and brown trout when compared with streams not affected by grazing (Wohl and Carline, 1996). Population declines were attributed to the increased sediment loads and composition of suspended sediments in the stream.

Fenced riparian buffers in Wisconsin can be grazed for a short duration during selective periods (up to 20 d per season; Bellows, 2001) and still minimize grazing damage. This practice allows farmers to utilize production from the riparian pasture and could also promote propagation of sensitive species such as buffalo clover, which typically grows along the edge between forest canopy and grasslands and requires periodic disturbance (USFW, 2003).

**Water Quality.** Lack of exclusion fencing permitted livestock to deposit urine and feces directly into streams resulting in elevated N

and P levels in Maryland (Shirmohammadi et al., 1997). In the Cannonsville, New York, watershed, 11,000 dairy cattle deposited 7% of all fecal deposits into pasture streams. This was a total deposition of 2800 kg of P in streams, and an additional 5600 kg of P was deposited within 10 m of streams (James et al., 2007). Recent efforts to exclude pastured cattle from streams as part of the Conservation Reserve Enhancement Program have already reduced in-stream deposition of fecal P by 32% (James et al., 2007). Cattle exclusion reduced mass loads of total-N fractions in the stream by 21% to 52% compared with grazed pasture in 2 of 3 yr in Alberta, Canada (Miller et al., 2010).

Nitrate plus nitrite (33%), total Kjeldahl N (78%), total P (76%), and sediment loads (82%) decreased following the installation of exclusion fencing and establishment of a riparian buffer in North Carolina (Line et al., 2000). They theorized that continued maturation of trees and other vegetation in the riparian strip increased N removal efficiency. The fenced buffer also decreased fecal coliforms (66%), enterococci (57%), turbidity (49%), and suspended sediment (60%) in the stream. A 20% to 31% reduction in total-N and a 17% to 26% reduction in suspended sediment at low-flow conditions were measured after installing exclusion fencing (Galeone, 2000).

Exclusion fencing reduced total load of suspended solids and N and P constituents due to reduced streambank erosion. Suspended sediment concentrations were reduced by 47% to 87% for base flow conditions following exclusion fencing, bank stabilization, and installation of rock-lined stream crossings along two Pennsylvania streams (Carline and Walsh, 2007). The decrease in concentration of suspended sediment was attributed largely to reduction in bank erosion and to a vegetation increase of nearly 50% following riparian restoration efforts. Concentrations of total suspended solids decreased by 75% to 83% at the study sites.

Cattle were identified as the primary source of steroid excretion in the USA, accounting for over 90% of the estrogens and over 40% of the androgens released yearly (Lange et al., 2002). The majority of the estrogen was excreted by pregnant cows (Lange et al., 2002; Shore and

Shemesh, 2003). Research regarding livestock distribution patterns in relation to hormone levels is sparse. Kolodziej and Sedlak (2007) detected steroids in 86% of samples from a California stream with unrestricted cattle access. They concluded that use of exclusion fencing to limit direct deposition of wastes into streams should be considered.

Limiting manure deposition in riparian areas reduces bacterial loads to streams. Laboratory experiments using a rainfall simulator showed a 95% reduction in bacterial loads if there was a minimum distance of about 2 m between the feces and the stream. Fecal bacteria can survive in manure deposits for over 100 d (Wang et al., 2002); thus the time horizon for potential introduction to a waterway, whether surface or subsurface, is lengthy. Once in the stream, bacteria survive in the bottom sediments, which function as reservoirs for the organisms (Van Donsel and Gelreich, 1971; Stephenson and Rychert, 1982). Clay-sized bottom sediments have been linked to greater survival rates (Burton et al., 1987; Sherer et al., 1992; Howell et al., 1995), a fact needing careful consideration in light of the increased sediment loads attributed to grazing.

**Hydrology.** Few studies have been conducted to determine changes in water quantity as a result of implementing exclusion fencing. Establishment of a 16-m wide riparian buffer protected by exclusion fencing reduced water discharge to the stream due to increased levels of evapotranspiration and infiltration of the riparian buffer while soil bulk density decreased and hydraulic conductivity increased (Line et al., 2000). These results correspond to work by Sartz and Tolsted (1974), who linked higher runoff volumes and peak flows with grazing. Following animal removal, runoff volumes returned to non-grazed conditions within a 3-yr period, which was attributed to vegetative recovery and improved infiltration. Grazing was simulated on runoff plots, and runoff decreased as vegetation and litter coverage increased (Hofmann and Ries, 1991). Grazing was also simulated on poorly and well-drained soils, and runoff volume generated from lightly grazed plots on poorly drained soils was similar to heavily grazed plots on well-drained soils (Butler et al., 2008). They concluded that grazing should be limited in riparian areas with poorly

drained soils as the runoff volume was linked to high levels of exported  $\text{NH}_4\text{-N}$  and total N.

**Stream Morphology.** Streams are not universal in their response to grazing or in their ability to naturally recover once grazing has stopped (Sarr, 2002). Therefore, the decision to install exclusion fencing should be based in part on the geomorphic characteristics of the stream. While monitoring continuously stocked pastureland in Ohio, Owens et al. (1989) found grazing increased sediment transport and

Fencing can be used to exclude livestock from streams and streambanks. Photo by Tim McCabe, USDA-NRCS.





A three- to six-fold increase in streambank erosion was associated with unrestricted grazing”

indicated exclusion fencing may be needed. When exclusion fencing was installed, annual sediment concentration was reduced by 57% and soil loss by 41% from 2.5 to 1.4 Mg ha<sup>-1</sup>. A three- to six-fold increase in streambank erosion was associated with unrestricted grazing as compared with streambanks protected by exclusion fencing. This translated into an estimated net erosion rate of 40 m<sup>3</sup> km<sup>-1</sup> yr<sup>-1</sup> of grazed streambank (Trimble, 1994).

Continuous, unrestricted, year-long stocking at high stocking rates in the eastern USA was implicated as a major factor causing stream widening (Trimble, 1994). Streambank erosion rates of 22 to 50 mm yr<sup>-1</sup> were measured when adjacent areas were grazed; this equates to an estimated erosion rate of 6 to 61 Mg km<sup>-1</sup> yr<sup>-1</sup> (Zaimes et al., 2008a). Phosphorus losses associated with the streambank materials were 3 to 34 kg km<sup>-1</sup> yr<sup>-1</sup>. No change was seen in stream cross-sectional area between reaches with excluded riparian areas and those without (Agouridis et al., 2005b); however, along the unrestricted reaches, localized streambank erosion occurred quickly in areas with frequent cattle movement and slowly in areas where cattle loitered.

### Other Livestock Distribution Options

Livestock distribution options such as supplemental feeding (e.g., salt, mineral, hay) and topography have not been examined in pasturelands, but supplemental feeding practices on rangeland can reduce cattle impacts in riparian areas (McInnis and McIver, 2001; Porath et al., 2002). Topography also affects cattle distribution (USDA-NRCS, 2003), and linkages have been found between slope and forage utilization rate.

### Summary and Recommendations: Livestock Distribution in the Landscape

Most livestock distribution on pasturelands literature addresses exclusion fencing and riparian buffers, with relatively little research on effects of shade, alternate water sources, and supplemental feeding. Research from rangeland systems suggests that each of these could be a beneficial best management practice for pasturelands. While exclusion fencing and riparian buffers can reduce negative effects of grazing livestock on stream ecosystems, farmers are often reluctant to adopt the practices

because of costs of installing an alternate water source and maintaining fencing (Barao, 1992; Soto-Grajales, 2002; Agouridis et al., 2005a; Zaimes et al., 2008a).

Adoption of best management practices is positively linked to information access and social networks with other farmers and agencies (Prokopy et al., 2008). Farmers who are most likely to incorporate management practices were younger with higher education levels and had larger acreage farms, greater amount of capital, and access to a larger labor supply. Such knowledge should aid conservationists in extending these practices to producers.

Riparian buffers are a component of exclusion fencing, but can also be used independently as a management tool. Riparian pasture can be grazed for up to 20 d per season with minimal damage, which allows farmers to utilize the area for production, while improving forage species mix and water quality (Bellows, 2001). Research is needed to understand the effects of livestock distribution on shallow groundwater quality and recharge, particularly in karst areas that are prevalent in pasturelands of the eastern USA (Veni, 2002). As noted by Owens et al. (2008), groundwater discharge has an appreciable effect on stream quality and flow. Thus, in smaller watersheds, where a large percentage of land use may be in one practice such as grazing, land use may have a greater effect on both stream water quality and flow.

### PURPOSE 4: REDUCE ACCELERATED SOIL EROSION, AND MAINTAIN OR IMPROVE SOIL CONDITION

Grazinglands typically have greater soil organic matter concentration than neighboring crop lands (Franzluebbers, 2005; Johnson et al., 2005). Soil organic matter is an ecological cornerstone by providing nutrients to plants, stability and water-holding capacity to soil, and energy to soil microorganisms. Through soil microbial processing of plant-derived organic matter, a long-term reservoir of nutrients accumulates along with gradual mineralization such that eutrophication of receiving water bodies is avoided (Franzluebbers et al., 2000a; Franzluebbers, 2008). Additionally, soil aggregates are built to store more

water for plant uptake and to withstand degenerative forces of erosion and compaction (Franzluebbbers et al., 2000b, 2001). Carbon and N are organically sequestered in soil to limit greenhouse gas emissions (Franzluebbbers and Stuedemann, 2001, 2002), and a diversity of soil organism communities develop to stabilize ecosystems against various perturbations (Franzluebbbers et al., 1999; Jangid et al., 2008).

### GRAZING INTENSITY

Optimum grazing intensity on pastures is needed to maintain vigorous vegetative cover, which is a key determinant in controlling soil erosion. High stocking rate results in a greater proportion of forage consumed than low stocking rate, and soil loss is expected to be greater under high than low stocking rate due to less vegetative and residue cover of the soil. The stocking rate at which soil loss exceeds a critical threshold of sustainability has not been determined, in general or in specific regions. However, high runoff and soil erosion can occur even on pastures with low stocking rate if vegetative cover is reduced due to animal behavior patterns, e.g., in loafing areas, along walking trails, and in animal-handling zones. Animal behavior is a key variable that makes grazinglands a more complex arena for ecological investigation than croplands because in croplands production and harvest are more uniformly distributed within fields.

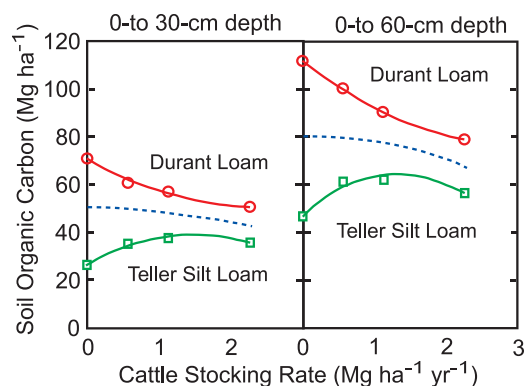
Literature describing soil erosion and soil condition responses to stocking rate in the humid regions of the USA is sparse. Far more data are available to compare soil erosion and soil condition between hay harvested and grazed perennial grass systems or cropped and perennial grass systems (Barnett et al., 1972; Giddens and Barnett, 1980; Sharpley and Smith, 1994; Franzluebbbers et al., 2000a, 2000b; Sharpley and Kleinman, 2003; Causarano et al., 2008).

In Oklahoma, Potter et al. (2001) reported soil organic C and N at the end of 10 yr of grazing with a range of stocking rates on two sites of degraded pasture. Pastures were initially dominated by annual ragweed and gradually became dominated by native grasses. On a Durant loam (30%  $\pm$  5% clay; Udertic

Argiustoll), soil organic-C declined with increasing stocking rate (Fig. 3.6) whereas on the neighboring Teller silt loam (17%  $\pm$  5% clay; Udic Argiustoll), soil organic-C increased slightly. These inconsistent responses occurred both within surface soil (0- to 30-cm depth), and deeper in the soil profile (to 60-cm depth). Stocking rate had a similar effect on total soil-N.

On a landscape dominated by Madison-Cecil-Pacolet soils (Typic Kanhapludults) in Georgia, a 12-yr grazing trial on Coastal bermudagrass (years 1–5) and bermudagrass overseeded with tall fescue (years 6–12) showed soil organic-C was maximum at a moderate stocking rate (Fig. 3.7). Response of soil organic-C and N deeper in the profile showed similar responses at the end of 5 yr (Franzluebbbers and Stuedemann, 2005) and were even more pronounced at the end of 12 yr (Franzluebbbers and Stuedemann, 2009). These results suggest that moderate to heavy stocking will optimize soil organic-C and N fractions compared with nonharvested or hayed management.

In Georgia total and particulate organic N in the 0- to 6-cm depth were greater under high than low stocking rate at the end of 4 yr (Franzluebbbers and Stuedemann, 2001), but at the end of 12 yr were not different between stocking rates throughout the soil profile (Franzluebbbers and Stuedemann, 2009). Extractable P, K, and Mg were not different

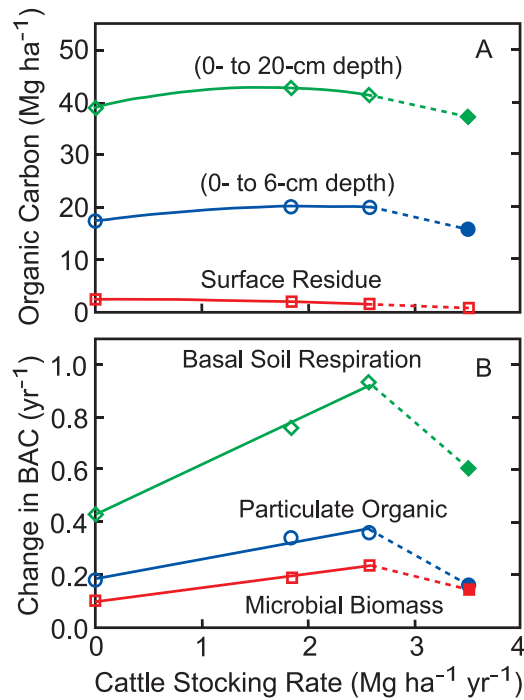


**FIGURE 3.6.** Content of soil organic-C at two depths following 10 yr of grazing management with different cattle stocking rates on Durant loam and Teller silt loam soils near Marietta, Oklahoma. Non-grazed pastures were achieved using exclosures. Adapted from Potter et al. (2001).

“Optimum grazing intensity on pastures is needed to maintain vigorous vegetative cover, which is a key determinant in controlling soil erosion.”



nutrient cycling within the pasture makes it possible to avoid the high demand for continuous nutrient input with hay harvest.”



**FIGURE 3.7.** (A) Content of soil and surface residue organic-C at the end of 5 yr of management. Adapted from Franzluebbers et al. (2001). (B) Relative annual change from baseline (0.0) in biologically active carbon (BAC) fractions of soil organic matter at a depth of 0–6 cm during 4 yr of management on Typic Kanhapludults near Farmington, Georgia. For both A and B, open symbols indicate no grazing and two stocking rates; filled symbols, forage removed as hay. Adapted from Franzluebbers and Stuedemann (2003a).

between stocking rate treatments during the first 5 yr, but tended to be somewhat greater with grazing than without grazing and much greater with grazing than with hay harvest (Fig. 3.8). Residual inorganic N in the upper and lower rooting zone followed the same pattern as other soil nutrients, but tended to decline with increasing stocking rate in samples below the rooting zone (Fig. 3.8). These results suggest that moderate to heavy stocking can improve soil chemical properties relative to nonharvested grass and that nutrient cycling within the pasture makes it possible to avoid the high demand for continuous nutrient input with hay harvest. Plant-essential (i.e., Mn, Cu, and Zn) and nonessential elements (i.e., Cd, Cr, and Pb) accumulated with cattle grazing compared with nonharvested or hayed areas. This indicated greater sorption of trace elements by soil organic matter, especially as

related to the dynamics of biologically active fractions (Franzluebbers et al., 2004b).

Stocking rate effects on soil organic matter and soil condition in the humid region of the USA have been determined to a much lesser extent than in the semiarid and arid regions of the USA (Milchunas and Lauenroth, 1993; Conant and Paustian, 2002; Derner et al., 2006), as well as in humid and arid regions of other countries (Greenwood and McKenzie, 2001; Bilotta et al., 2007). In a review of stocking rate effects on soil aggregation, Greenwood and McKenzie (2001) reported that most studies ( $n = 8$ ; outside the humid USA) found animal grazing generally reduced aggregation. Most changes were small at low stocking rate and greater with intensive treading, which causes compaction. Greenwood and McKenzie (2001) cited 22 studies from around the world, most of which found an increase in bulk density with increased treading.

Although increased stocking rate generally compacts soil, the extent may be mitigated by controlling the timing and intensity of grazing and knowing whether the soil surface is firm enough to withstand the traffic. Penetration resistance may be a more discerning soil response to the impact of animal treading than soil aggregation or bulk density. Long-term studies are needed on stocking rates with measurements of soil penetration resistance, bulk density, and aggregation at different times of the year and at different durations of stocking rate treatments.

### Summary and Recommendations: Grazing Intensity

Establishment of pastures helps reduce soil erosion and improves soil quality on previously degraded cropland. Limited evidence also shows that grazing at moderate levels can further increase environmental benefits, in addition to the important economic return to producers. Some evidence in the humid USA suggests that overgrazing can lead to increased soil erosion, and reduction in soil condition. Literature outside the humid USA supports the concept that excessive stocking rate leads to increasing soil erosion and declining soil quality. A great need exists for establishing a comprehensive grazing intensity study (soil, water, air,

plant, and animal responses) in one or more locations within the humid USA.

### STOCKING METHOD

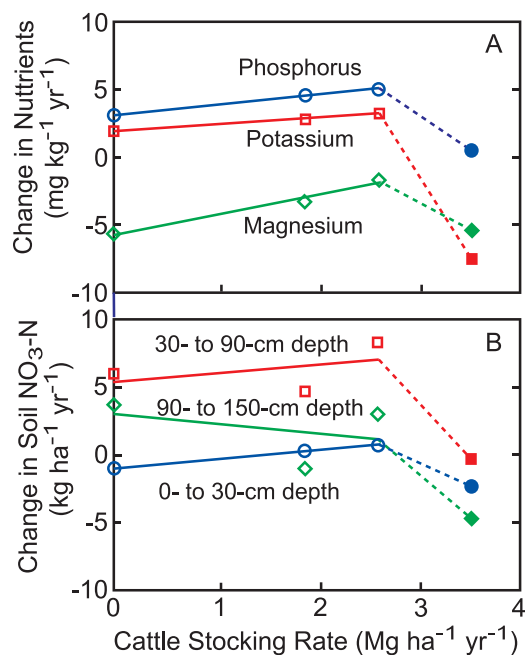
Rotational stocking in the humid USA should provide more uniform forage consumption across pastures and allow sufficient rest of forages to promote greater production (Chestnut et al., 1992; Hoveland et al., 1997). Pastures with greater plant production via an improved stocking method would be expected to have lower soil erosion and greater soil quality. While intuitive, essentially no data are available in the scientific literature from the humid region of the USA to support a claim for positive effects of rotational stocking alone, or in comparison with continuous stocking, on soil erosion or soil condition.

### Summary and Recommendations: Stocking Method

An urgent need exists to obtain information on how and to what extent stocking method affects soil erosion, soil condition, and soil C sequestration in the humid USA, especially since recommendations without a science base could mislead landowners, policy makers, and agro-environmental stakeholders. Although scientific rationale may be limited for additional studies comparing stocking methods from a plant or animal response perspective, this is not the case regarding soil and environmental issues. This deficit in information suggests a need for such comparisons at several strategically selected sites throughout the humid pastureland regions of the USA. Teams of the best scientists nationally in the areas of soil, plant, water, wildlife, and animal response should be assembled to coordinate these studies. If so, the treatment selection and response measurement should be done in a manner that will generate conclusive and transferable results as well as data for modeling. Conclusions from this comprehensive work would serve as an authoritative guide to future prescribed grazing recommendations.

### SEASON OF GRAZING AND DEFERMENT

The capacity of soil to withstand compaction forces of animal treading, resulting in significant deformation, destabilization, and

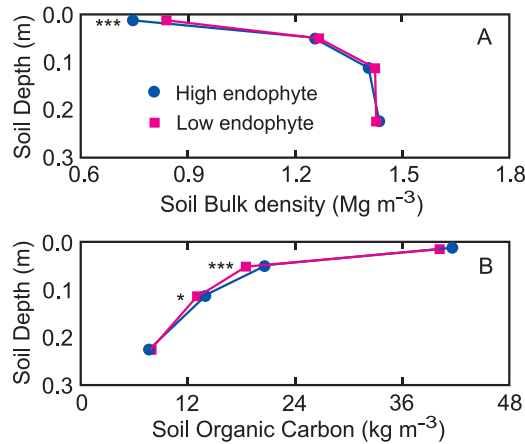


**FIGURE 3.8.** (A) Effects of 5 yr of grazing management on changes from the baseline condition (0) of extractable phosphorus, potassium, and magnesium in the surface 15 cm of Typic Kanhapludults near Farmington, Georgia. Adapted from Franzluebbers et al. (2002, 2004a). (B) Changes in residual NO<sub>3</sub>-N in the upper rooting zone (0- to 30-cm depth), lower rooting zone (30- to 90-cm depth), and below the rooting zone (90- to 150-cm depth). Adapted from Franzluebbers and Stuedemann (2003b). For both A and B, open symbols indicate no grazing and two stocking rates; filled symbols, forage removed as hay.

loss of infiltration capacity, can be exceeded especially under wet conditions (Bilotta et al., 2007). Soil can be expected to be saturated during much of the winter in the southeastern USA and in the spring in the central and northeastern USA. These seasons are therefore the most vulnerable times for soil to experience severe animal trampling effects. Intuitively, deferring grazing to periods of limited active forage growth (e.g., winter and spring) might contribute to increased soil compaction. However, allowing forage to accumulate to a high level prior to grazing might be beneficial to controlling erosion by providing a longer period of forage and residue cover. Grazing of winter cover crops may also be an effective farm-diversity strategy, but the effects on soil erosion control and soil condition need to be quantified.



Organic matter-rich surface soil absorbs compactive forces much like a sponge, often rebounding in volume once forces are removed.”



**FIGURE 3.9.** Depth distribution of soil bulk density (A) and soil organic carbon (B) at the end of 8 to 15 yr of grazing tall fescue containing low or high levels of endophyte infection on a Cecil sandy loam (Typic Kanhapludult) near Watkinsville, Georgia. Adapted from Franzluebbers et al. (1999). \* and \*\*\* indicate means at that depth are different at the 0.05 and 0.001 probability levels, respectively.

In the southern USA, perennial cool-season grasses are often grazed during late winter and throughout spring during typically wet conditions. However, because of active forage growth, soil can also dry quickly, and trampling may not always cause damage. In Georgia soil organic-C and N were greater under long-term stands of cool-season tall fescue (typically grazed in spring and autumn) than under warm-season bermudagrass (typically grazed in summer) (Franzluebbers et al., 2000a). Soil bulk density under grazed tall fescue on Cecil sandy loam (Typic Kanhapludult) in Georgia did not show signs of excessive compaction, partly due to the long-term accumulation of soil organic matter at the soil surface (Fig. 3.9), which mitigated compactive forces. Organic matter-rich surface soil absorbs compactive forces much like a sponge, often rebounding in volume once forces are removed. Effects of winter grazing of deferred growth may be different in colder areas; frozen soil may resist compaction, but nutrient runoff may become more important (Clark et al., 2004).

Annual cool-season forages are often planted as a cover crop following summer crops or sod-seeded into perennial grass pastures in the southeastern USA. On a Typic Kanhapludult in

Georgia, soil bulk density at the end of 3 yr of winter grazing of rye by stocker cattle was the same ( $1.50 \text{ Mg m}^{-3}$ ) as when the cover crop was not grazed (both following full-season soybean) in a system using conventional tillage to remove compaction on a biannual basis (Tollner et al., 1990). However, when no-tillage management was used every year the bulk density was greater ( $1.60$  vs.  $1.52 \text{ Mg m}^{-3}$ ) when the cover crop was grazed than not grazed.

In a pasture-crop rotation study in Georgia, soil bulk density during 5 yr of winter grazing of rye by cow-calf pairs was not different from that of non-grazed winter cover-cropping (Fig. 3.10). Soil aggregation and penetration resistance were also not affected by grazing of cover crops. Water infiltration was reduced 28% by grazing of winter cover crop compared with non-grazed rye, but was reduced only 19% by grazing of summer cover crop compared with non-grazed pearl millet (Franzluebbers and Stuedemann, 2008b). Soil organic-C and N fractions were little affected by grazing of cover crops, in either summer or winter (Franzluebbers and Stuedemann, 2008a).

In Coastal Plain soils prone to hardpan development in the E horizon, soil compaction in long-term cropped soils is a continual concern due to inhibition of adequate root penetration deep into the soil profile. Introducing cattle grazing onto winter wheat or cover crops has led to soil compaction and restricted plant growth. On a Plinthic Paleudult in South Carolina, stocker cattle grazing winter wheat planted after disking and chisel-plowing resulted in greater soil penetration resistance with a linear increase related to grazing duration (Worrell et al., 1992). Wheat grain yield declined with longer grazing time, but cattle weight gain increased. On a Plinthic Kandiudult in Alabama, soil hardpan development was alleviated best with paratilling, even with winter grazing of cover crops following cotton or peanut in summer (Siri-Prieto et al., 2007).

On three soils in Oklahoma (Mollic Albaqualf and two Udic Argiustolls), soil bulk density and penetration resistance were greater following grazing of wheat (conventionally tilled) to early joint stage than when wheat was not grazed (Krenzer et al., 1989). Greater bulk density

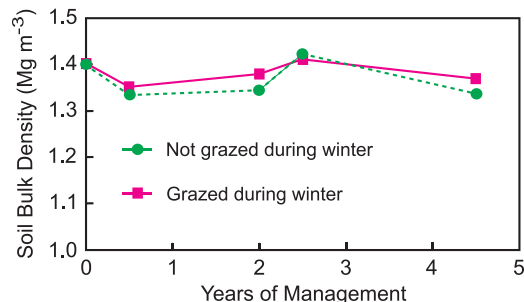
occurred to a depth of 9 cm in two soils and to 21 cm in a third soil. Winter grazing of wheat increased penetration resistance to depths of 16, 18, and 28 cm, respectively.

### Summary and Recommendations: Season of Grazing and Deferment

Animals grazing forage on unstable soil, attained either through soil loosening to ameliorate previous compaction or from excessively wet conditions, can have detrimental effects on soil bulk density, soil aggregation, and penetration resistance, which in turn negatively affects productivity and environmental quality (Bilotta et al., 2007). Although some indirect evidence in the humid USA, especially in the South, is available to make this claim, a great need still is seen for more comprehensive studies to understand the multitude of soil changes (e.g., soil erosion, soil structure, soil organic matter, and soil nutrients) in response to stocking method, season of grazing, and duration of deferment. For example, it is unclear how these practices affect long-term accumulation of soil organic matter and what this impact might be on subsequent soil quality, environmental outcomes, and forage and animal productivity. Studies should be expanded to include soil responses in riparian areas.

### TYPE AND CLASS OF LIVESTOCK

Little comparative evidence exists in the humid USA to assess the impact of livestock type and class on soil erosion and soil condition. Further, many other factors (such as climate, soil type, forage type, management practices, etc.) could confound interpretations from a group of isolated projects studying different types and classes of livestock. As noted by Bilotta et al. (2007) in their excellent review of animal grazing effects on soils, vegetation, and surface waters, data from outside the region or even country may be useful, but data must be used with caution because of the many differences in climate, soil type, vegetation, and grazing management style that could limit transferability. There is a great need to determine the impact of single-species, single-age, mixed-species, and mixed-age livestock effects on soil erosion and soil condition in the humid USA. If data were available, modeling may help with transferability by sorting out the variables and their effects.



**FIGURE 3.10.** Changes in soil bulk density (0- to 12-cm depth) during the first 5 yr of cropping with grain sorghum or corn during summer and a cover crop of rye that was not grazed or grazed by cow-calf pairs during winter. Crops were grown using no-tillage management on a Cecil sandy loam (Typic Kanhapludult) near Watkinsville, Georgia. Grain sorghum and corn data were averaged. Treatment means within a sampling time were not different between not grazed and grazed systems at the 0.05 probability level. Adapted from Franzluebbbers and Stuedemann (2008b).

### LIVESTOCK DISTRIBUTION IN THE LANDSCAPE

Cattle tend to congregate around shade and water sources and, therefore, can affect the distribution of manure and nutrients in pastures. Short-term grazing studies in small paddocks at several locations in the humid USA have shown greater concentration of P and K near shade and watering areas than farther away (West et al., 1989; Wilkinson et al., 1989; Mathews et al., 1994a). Longer-term studies have shown greater concentration of inorganic nutrients (N, P, K, and Mg) and organic constituents (e.g., total, particulate, and microbial C and N fractions) near shade and water sources than farther away (Franzluebbbers et al., 2000a; Schomberg et al., 2000; Franzluebbbers and Stuedemann, 2010).

In Georgia, soil organic C at the end of 5 yr of Coastal bermudagrass management was greater nearest shade and water sources at surface depths to 12 cm, but not below. Total C in soil and stubble was nearly 4 Mg C ha<sup>-1</sup> greater near shade than farther away; a large difference considering the average pasture stock of C was about 43 Mg ha<sup>-1</sup> (Franzluebbbers and Stuedemann, 2010). In tall fescue pastures grazed by cattle for 8 to 15 yr, soil organic-C was greatest near shade and water sources and declined logarithmically with increasing



An important ecosystem service of pastureland is providing wildlife habitat and food supply.”

distance. Soil organic-C to a depth of 30 cm was 46.0 Mg C ha<sup>-1</sup> at 1 m from shade, 43.2 Mg C ha<sup>-1</sup> at 10 m from shade, 39.9 Mg C ha<sup>-1</sup> at 30 m from shade, 40.5 Mg C ha<sup>-1</sup> at 50 m from shade, and 39.4 Mg C ha<sup>-1</sup> at 80 m from shade (Franzluebbers et al., 2000a). The zone within a 10-m radius of shade and water sources became enriched in soil organic-C, most likely because of the high frequency of cattle defecation and urination, which would increase fertility level and subsequent forage growth (Dubeux et al., 2006).

To minimize the probability of N contamination of surface and groundwater supplies (since total N also increased with soil organic-C), shade/water sources should be moved periodically, positioned on the landscape to minimize flow of percolate or runoff directly from these areas to water supplies, and avoided during routine fertilization. In Pennsylvania livestock concentration areas caused an increase of soil P within a 20- to 40-m radius, which led to greater P concentration in runoff (Sanderson et al., 2010). The authors stated that if livestock concentration areas were surrounded by sufficient vegetation, risk of surface water quality deterioration could be mitigated.

#### **PURPOSE 5: IMPROVE OR MAINTAIN THE QUANTITY AND QUALITY OF FOOD AND/OR COVER AVAILABLE FOR WILDLIFE**

An important ecosystem service of pastureland is providing wildlife habitat and food supply. Within the pastureland context, research quantifying the effects of prescribed livestock grazing strategies on wildlife is limited. Most research has focused on wildlife responses to grazing intensity. Of the 52 wildlife papers reviewed, 34 (65%) reported grazing intensity responses. Avian responses to prescribed grazing strategies in pastureland were studied in 38 of 52 papers (73%), but this assessment will also include invertebrates, reptiles, amphibians, fish, and mammals.

Implementing a grazing management plan to enhance wildlife habitat requires an interdisciplinary approach because such a plan depends upon knowledge of plant community dynamics, life cycle and habitat requirements of affected wildlife species, and potential effects on

livestock (Vavra, 2005). Further, Vavra suggests that any habitat change made for a featured species may create adverse, neutral, or beneficial changes for other species, and development of a grazing management plan on a field scale is rarely sufficient; understanding complementary grazing practices on a landscape scale is required.

#### **GRAZING INTENSITY**

Grazing intensity is widely viewed as the grazing management strategy having the greatest impact on plant and livestock responses. Thus, it is reasonable that wildlife response to livestock grazing intensity has been evaluated more than to any other prescribed grazing strategy.

#### **Birds**

Throughout North America, populations of birds that rely on grasslands are declining faster than any other type of bird, and in Pennsylvania 82% of grassland-associated avian species have declined in number in the last three decades (Giuliano and Daves, 2002). The reasons are not known, but greater grazing intensity is thought to play a role. In Great Britain the sheep population has more than doubled since 1950, and associated severe grazing pressure has been implicated in changes in vegetation structure and bird populations (Evans et al., 2005). Grazing intensity can affect avian populations by altering plant species composition, vegetation cover, litter mass, food supply, predator populations, and degree of nest disturbance. In a review of livestock grazing impacts on sage grouse habitat, 10 of 17 studies showed direct effects from livestock grazing, but the authors concluded that indirect effects of grazing on habitat were of even greater significance (Beck and Mitchell, 2000). Both direct and indirect effects of grazing intensity on avian abundance, species richness, nest site selection, and nesting success are assessed.

*Avian Abundance and Species Richness.* In the St. Lawrence River area of Quebec, Canada, grazed and moderately grazed grassland contained six times more birds than intensively grazed grassland (10.4, 11.7, and 1.6 birds ha<sup>-1</sup>, respectively) (Bélanger and Picard, 1999). No species or species group showed a preference for intensively grazed pasture, and the authors

concluded that stocking rate exceeding 1 cow ha<sup>-1</sup> is detrimental to avian abundance. In Scotland low-intensity mixed grazing by cattle and sheep increased the abundance of meadow pipit due to its effect on food availability (Evans et al., 2006b). Arthropod abundance and species diversity increased with greater habitat heterogeneity (Dennis et al., 2008). In a review of grazing effects on habitat for a wide range of birds, Derner et al. (2009) recommended against restriction of grazing and argue for use of livestock as “ecosystems engineers.” They indicate that using heterogeneity-based management, instead of emphasizing exclusively uniform use of vegetation, can alter vegetation structure and improve habitat for grassland birds.

The relationship between avian abundance and grazing intensity varies among bird species (Durant et al., 2008). Sward structure preferences also exist, with some avian species preferring more and others less variation in structure. In Queensland, Australia, it was hypothesized that avian foraging height was a good predictor of bird sensitivity to livestock grazing (Martin and Possingham, 2005). Their model predicted that 31 bird species would decline with increased grazing intensity, and this was confirmed by field observations. They concluded that instead of searching for patterns of population change in response to specific grazing treatments, ecologists should consider the mechanisms underlying the change, one of which is avian foraging height.

In another Australian woodland study, any level of livestock grazing was detrimental to some birds, particularly the understory-dependent species (Martin and McIntyre, 2007). Provided that trees were not cleared, however, a rich and abundant bird population existed under moderate levels of grazing, but high grazing intensity resulted in a species-poor bird assemblage. In a review of grazing effects on sage grouse habitat, both positive and negative effects of grazing by cattle were found (Beck and Mitchell, 2000). Periodic grazing was useful to remove mature grass and rejuvenate forbs that are a food source, but high grazing intensity eliminated most forbs.

**Nesting Site Selection.** In Quebec, Canada, nest density was 0.3, 0.5, and 0.05 nests ha<sup>-1</sup>,

respectively, for non-grazed, moderately grazed, and intensively grazed common pastureland (Bélanger and Picard, 1999). Stocking rates exceeding 1 cow ha<sup>-1</sup> were detrimental to the presence of birds that frequent this area.

During the spring nesting season of wading birds in France, fields with low grazing intensity were occupied by more birds than the landscape average (Tichit et al., 2005). Different species of waders showed different preferences to grazing intensity, however, and the authors highlight the importance of maintaining a variety of grazing regimes if conservation of waders was to be achieved at the community level.

In Montana plots not grazed by cattle had reduced forb cover, greater litter cover, greater litter depth, and increased ratings of visual obstruction for birds (Fondell and Ball, 2004). Nest density was most highly correlated with high visual obstruction rating. In Louisiana mottled ducks preferred to nest where vegetation height was greater than at random points within the habitat (Durham and Afton, 2003), and it was recommended that stocking rate and timing of grazing be managed to promote tall, dense stands during the March–June nesting season.

**Nesting and Reproductive Success.** In Kentucky pastures were not grazed or were grazed by cattle at 1 animal unit ha<sup>-1</sup> to determine effects of grazing on grasshopper sparrow (Sutter and Ritchison, 2005). Clutch sizes averaged 4.5 and 3.9 in non-grazed and grazed areas, respectively, and nest success was 70% in non-grazed vs. 25% in grazed swards. There was greater invertebrate biomass, more litter, and taller and denser vegetation in non-grazed areas. Most unsuccessful nests were depredated, and higher predation rates were attributed to less concealment in grazed areas. The authors attributed reproductive success in non-grazed areas to greater availability of prey and greater concealment from predators resulting in less nest disturbance.

In Montana nest success was similar between grazed and non-grazed plots for two bird species, but greater in non-grazed areas for two other species, due to less predation and less trampling (Fondell and Ball, 2004). The



heterogeneity-based management, instead of emphasizing exclusively uniform use of vegetation, can alter vegetation structure and improve habitat for grassland birds.”



...management alternatives that avoid intensive grazing during the breeding season would benefit many bird species.”

authors suggested that management alternatives that avoid intensive grazing during the breeding season would benefit many bird species. In west Texas nest losses due to trampling were directly proportional to stocking rate (Koerth et al., 1983). In Louisiana successful nests of mottled ducks were found in areas with a greater number of plant species and greater vegetation density than unsuccessful nests (Durham and Afton, 2003). Mammalian predators caused most failures, and the authors recommended managing stocking rate and timing of grazing to promote tall, dense stands during the nesting season.

In England black grouse reproductive success was compared in pastures where sheep were stocked at regional average rates and a third of normal levels (Calladine et al., 2002). Proportion of hens retaining broods late in the chick-rearing period was 54% and 32% for low vs. normal stocking rate, indicating that manipulation of grazing intensity can contribute to conservation of black grouse. In Scotland sheep were stocked at rates of 2.7, 0.9, and 0.6 ewes ha<sup>-1</sup>, or swards were not grazed to evaluate effects on meadow pipit (Evans et al., 2005). The highest stocking rate was associated with the smallest eggs and lowest stocking rate with the largest eggs, but non-grazed plots had smaller eggs than lightly grazed plots. There was no effect of egg size on fledgling success. The authors suggested that grazing intensity affected the food supply and the amount of resources that the parents could allocate to egg production.

As with avian abundance, nesting success is not always affected by grazing intensity. In Idaho (Austin et al., 2007) and Oregon (Ivey and Dugger, 2008), no difference was found in nesting success of the sandhill crane due to livestock grazing. In both environments the major factor affecting nesting success was water level and its effect on predation. In Missouri nest success of the prairie chicken was related to amount of litter and presence of forbs and woody cover (McKee et al., 1998). Nest success declined with increasing woody cover, with decreasing grass and forb cover, and when litter cover was above 25%. More litter delayed grass growth, reduced nest cover, and increased small mammal populations resulting in increased predation.

## Mammals

Field vole abundance in pastureland is important because of their role as a food source for other species and because they damage young trees by chewing on bark (Evans et al., 2006a). Vole abundance was greater in plots with low vs. high stocking rate and with low stocking rate of sheep plus cattle compared with sheep alone. Low stocking rate favored voles because of greater food resources and greater cover to protect from avian predators.

In Oregon several species of small mammals had lower abundance in heavily vs. lightly grazed sites, and biomass of small mammals was lower under heavy grazing (Johnston and Anthony, 2008). Preference was evident for vegetative cover, and a reduction in grazing pressure was recommended to increase small mammal biomass.

In Greece lightly grazed pastures were less preferred by brown hares compared with moderately grazed ones, and non-grazed pastures were less preferred by hares than grazed ones (Karmiris and Nastis, 2007). Greater use of moderately grazed pastures by hares was associated with reduced herbage height and density, allowing hares to see approaching predators.

Cattle grazing intensity (0%, 50%, 70%, and 90% removal of standing crop) of rough fescue during autumn in Montana did not alter pasture species composition for subsequent grazing in spring by elk and deer (Short and Knight, 2003). The 50% and 90% removal treatments reduced live herbage mass the subsequent spring but not in summer. It was recommended that autumn grazing remove 70% of herbage mass to reduce standing dead material the subsequent spring.

## Reptiles

The spur-thighed tortoise is an endangered reptile present in semiarid and Mediterranean agro-ecosystems where livestock grazing occurs in Spain (Anadon et al., 2006). The main threat to the tortoise is habitat loss and fragmentation. Tortoises selected areas with intermediate annual grass cover and rejected areas with low and high grass cover.

## Invertebrates

Foliar arthropods are an important component of bird diets. Increasing stocking rate of sheep and replacing cattle with sheep have been associated with declines in many upland birds in Scotland, and a link may exist between declines in bird populations and availability of arthropod prey (Dennis et al., 2008).

In Scotland arthropod biomass was lower in areas grazed with sheep at the commercial density than at one-third that density during 3 yr (Dennis et al., 2008). In Sweden insect species richness was negatively affected by increasing grazing intensity and decreasing sward height (Söderström et al., 2001). In the Northeast USA, low stocking rates and high soil moisture were most highly positively correlated with number of macroinvertebrates (Byers and Barker, 2000).

Unlike many insect groups, spiders do not have strong host-plant associations (Bell et al., 2001), so sward structure of grasslands is more important than plant species present. Low grazing intensity leads to deeper litter layers and more architecturally diverse vegetation, which increases spider diversity, especially the number of web spinners. Rigid vegetation favors web spinners, so livestock avoidance of certain weed species provides structure for webs. Dung spots and other products of animal grazing encourage tall vegetation that provides structural support for webs. Grazing at low intensity appears to be preferable for most spiders, and a mosaic of short and taller patches may benefit spiders. In heavily grazed areas, e.g., by sheep, provision of some areas not closely grazed to allow accumulation of litter provides good habitat for spiders.

The effects of stocking rate on habitat score of water bodies and macroinvertebrate populations were determined on five first-order western Virginia streams (Braccia and Voshell, 2006). Habitat score decreased from non-stocked to intermediate grazing intensity (154 cattle ha<sup>-1</sup>) and remained relatively unchanged with heavy and very heavy grazing intensities (2.1 and 2.9 cattle ha<sup>-1</sup>, respectively). The physical habitat metrics of suspended sediment and substrate homogeneity in water were the largest drivers of macroinvertebrate

populations. In a New Zealand riparian area, intensive grazing reduced streamside vegetation and increased bank damage, thus increasing stream temperatures and in-stream sedimentation. This, in turn, negatively influenced macroinvertebrate communities (Quinn et al., 1992).

## Summary and Recommendations: Grazing Intensity

The effect of grazing intensity on wildlife has received far more attention than any other grazing strategy, and most research has focused on avian response. The literature supports the conclusion that grazing intensity affects avian species abundance and richness, nest site selection, and nesting success. High grazing intensity reduced avian abundance due to loss of preferred habitat for nesting, destruction of nests due to trampling, and fewer invertebrate food sources (Fuller and Gough, 1999).

In some cases, low grazing intensity positively affects bird populations because of less trampling damage of nests by livestock and an increase in voles and other small mammals that serve as food for owls and raptors, but it can also increase nest predation of ground-nesting birds as a result of greater population of small mammals. Söderström et al. (2001) indicated that the importance of landscape composition for mobile organisms, such as birds, implies that management strategies should focus on providing diverse habitats within the wider countryside and not exclusively on single pastures or the grazing management of those pastures.

Clearly, selecting the proper grazing intensity should be a primary focus in developing and carrying out management plans for agroecosystems in which livestock production and wildlife preservation are concurrent objectives. The literature is equally clear, however, that responses to grazing intensity can vary widely among wildlife species. Thus, choice of grazing intensity must be evaluated within the context of what management practices benefit the broad array of wildlife present in the ecosystem and not only a high-profile species.

Further, indirect effects of grazing intensity can be as important, or in some cases more



...grazing intensity affects avian species abundance and richness, nest site selection, and nesting success.”



Riparian buffer strips in combination with fencing can be used to exclude or limit livestock access to riparian areas, improving water quality and wildlife habitat. Photo by Carmen Agouridis, University of Kentucky.

important, than direct effects on target wildlife populations. Indirect effects can be mediated through changes in vegetation abundance or structure, plant sources of food, water quality, and abundance of prey and predators. Although excessive grazing intensity is clearly detrimental, an argument for allowing grazing in the landscape can be made based on the concept of livestock as “ecosystems engineers” that can alter vegetation structure in positive ways and improve habitat for grassland birds (Derner et al., 2009).

In a review of North American grasslands, Frisina and Mariani (1995) suggest that grazing management strategies should focus on sustaining healthy vegetation and ensuring the presence of wildlife species or communities that play a role in ecosystem dynamics. Long-term management practices should allow only base-line or “natural” levels of soil erosion and maintain good

water quality, with a broad ecosystem focus instead of meeting the needs of one or two charismatic wildlife species and a particular class of livestock. Grazing intensity is a very important prescribed grazing tool in achieving these objectives.

### STOCKING METHOD

Only eight studies were found that examined the effects of stocking method of pastureland on macroinvertebrate, small mammal, and bird responses. The plant community is closely linked to mammalian and avian populations, and as such the effects of stocking method on vegetation response can have significant indirect impacts on habitat selection and reproductive success.

### Birds

In Saskatchewan, Canada, no difference was found between season-long and rotational stocking in duck nest success (25% vs. 20%)

(Ignatiuk and Duncan, 2001). Residual vegetation did not differ among treatments. Nest success in pastures was greater than that in cultivated fields, suggesting that expanding area of pasture may increase duck populations. They concluded that cattle stocking rate exerts a greater influence on vegetative response than stocking method.

In southwestern Wisconsin, grassland bird species richness, dominance, and density were compared on rotationally and continuously stocked riparian areas and on cropland with a 10-m non-grazed buffer strip (Renfrew and Ribic, 2001). No difference was seen in bird responses among land-use types. Rotational stocking did not support more grassland birds than continuous stocking. Instead, bird density was related to vegetation structure, with higher density found on sites with deeper litter, which generally were the non-grazed buffer strips.

In west Texas, loss of nests due to cattle trampling was 15% and 9% under continuous and rotational stocking, respectively, and was directly proportional to stocking rate, suggesting that stocking method had little effect (Koerth et al., 1983). In southwestern Wisconsin, beef heifers on pasture were rotated each day, every 4 d, or every 7 d to determine if stocking method affected percent trampling of simulated bird nests (Paine et al., 1996). Nest survival (new nests were placed before each grazing cycle) after eight grazing events per treatment averaged 25% and was not affected by treatment. Nest destruction decreased with increased vegetation height, density, and percent cover. The authors suggested that better nest protection can be achieved by allowing cattle grazing when forage is plentiful and leaving a large amount of residual forage.

In Canada, early-hatched waterfowl are more likely than late-hatched to enter the breeding population, so a study was conducted to determine factors that favored success of early-season nests (Emery et al., 2005). Managed cover types (especially delayed hay production) provided greater nesting success than unmanaged cover types (13% vs. 5%). The authors suggested that managers can influence growth of the breeding population through restoration, protection, or management of

nesting cover. Rotational stocking and delayed grazing were not better than unmanaged grazing.

### Small Mammals

In Wisconsin both abundance and species richness of small mammals were greater on buffer strips than on both continuously or rotationally stocked riparian areas, and stocking methods were not different (Chapman and Ribic, 2002). No evidence was found that small mammals responded to the development of greater cover during rest periods of rotational stocking or that conversion from continuous to rotational stocking had significant influence on small mammal communities in riparian areas. Conversion of land from grain to grass production, however, benefited small mammal communities.

### Macroinvertebrates

In Wisconsin continuous stocking of riparian buffers negatively affected macroinvertebrate assemblages, but those present had a high tolerance for organic pollutants (Weigel et al., 2000). Woody buffers supported species with a low tolerance for organic pollutants while rotationally stocked pastures and grass buffers had species with intermediate tolerance. When grazing occurred along Minnesota streams, impairment of water quality was greater at sites stocked continuously than rotationally (Sovell et al., 2000). No difference was seen in macroinvertebrate populations, however, between continuous and rotational stocking.

### Summary and Recommendations: Stocking Method

A limited number of studies have evaluated effects of livestock stocking methods on wildlife. With the exception of certain riparian macroinvertebrate assemblages, which are responsive to water quality changes due to stocking method, choice of stocking method did not have a significant effect on wildlife responses. Because of the limited data available, further studies are warranted, as was elaborated in the soil response section of this chapter. Based on the literature available at present, choice of livestock grazing intensity on pastureland appears to be more critical for success of wildlife than is choice of stocking method.



Conversion  
of land from  
grain to grass  
production...  
benefited  
small mammal  
communities.”



Increasing use of warm-season grasses...was recommended to support increased bird populations.”

### SEASON OF GRAZING AND DEFERMENT

Seven studies assessed the effect of season of pastureland grazing on wildlife responses. Six of the studies focused on avian species with emphasis on nest site selection and nesting success.

#### Avian Nest Site Selection and Nesting Success

Durant et al. (2008) reviewed livestock grazing effects on sward structure and the effect of timing of grazing on breeding wader birds. Early-spring-nesting birds were primarily affected by the high intensity of grazing during the previous autumn that reduced spring forage growth. Later-nesting species were more likely to be dependent on spring grazing patterns. Restricting livestock grazing or using reduced stocking rates in April through May is recommended so birds do not avoid areas where livestock are present or so livestock do not disturb nests. They concluded grazing may have, according to the season and bird species, positive or negative effects on bird breeding success. They noted that heterogeneity on a larger spatial scale is often important to site selection, so results also depend on factors beyond the individual pasture level.

In North Dakota nest density of upland sandpipers was lower for treatments where cattle were present during the nesting season (spring, both spring and autumn, and season-long grazing), but treatment did not affect nesting success (Bowen and Kruse, 1993). They recommended that areas with breeding populations of upland sandpipers include a complex of pastures under various management practices, including those that are not disturbed during spring.

In California nest density for various ducks in summer and geese and sandhill cranes in winter was measured in pastureland that was not grazed or was rotationally stocked with cow-calf pairs from 1 July through 1 November (Carroll et al., 2007). Nest initiation occurred in March through May, but all were inactive by 1 July when grazing began. Rotational stocking during the grazing season provided short, grassy vegetation that favored nesting by geese and cranes during the following winter, and still allowed vegetation to recover sufficiently for

the beginning of duck nesting in late March. Grazed sites had greater nest density.

Grazing during the late spring nesting period reduced herbaceous cover that is critical to concealing sage grouse nests from predators (Beck and Mitchell, 2000). Tall grass cover was greater at successful nests than depredated nests. It was concluded that sage grouse prefer canopy cover of tall grasses (> 18 cm) and shrubs for nesting, forbs and insects for brood rearing, and herbaceous riparian areas for late-season foraging (Crawford et al., 2004). Light to moderate grazing in the early season can promote forb abundance in both upland and riparian habitats that favor grouse. More intensive grazing can allow invasion by undesirable plant species.

The decline in grassland bird populations in Pennsylvania was associated with widespread use of cool-season grasses that are mowed or grazed during early April to late June, when most grassland birds are nesting (Giuliano and Daves, 2002). When a portion of the farm was planted to warm-season grasses, 42 avian species were found in warm-season and 30 species in cool-season fields. Abundance of birds was 1.6 times greater in warm- than cool-season grass fields, nesting success was 1.3 times greater, and fledge rates were 1.8 times greater. Warm-season pasture provided greater cover during the nesting period and lower disturbance rates. Increasing use of warm-season grasses in the region was recommended to support increased bird populations.

#### Invertebrates

In Alberta, Canada, total invertebrate biomass was greatest during late-season and all-season grazing as compared with early-season grazing (Scrimgeour and Kendall, 2003), which was attributed to the presence of large species in late season. Total density changed little among treatments, which the authors attributed to the short duration (2 yr) of the study. They hypothesized that a longer time frame would be required to produce changes in invertebrate food resources before increases in invertebrate numbers could be realized. More studies of longer duration are needed to determine effects of timing of grazing on invertebrates.

### Summary and Recommendations: Season of Grazing and Deferment

Most studies on effects of season of grazing on wildlife assessed the effect of timing on vegetation characteristics at potential avian nesting sites or on nesting success. Desirable site characteristics vary among avian species, but heterogeneity in sward structure at the landscape scale can provide a wider range of sward characteristics for nest site location. Incorporating additional pastureland species, e.g., warm-season grasses in temperate regions, provides variation in sward structure within the landscape, and differences in seasons of growth of these species make it relatively easy to vary the timing of grazing in support of wildlife populations.

### TYPE AND CLASS OF LIVESTOCK

Only two papers were found that addressed the role of type and class of livestock on wildlife. Both papers focused primarily on effects of livestock species on sward heterogeneity and its subsequent effect on population of invertebrates that are important prey for some grassland birds. In Scotland increasing stocking rate of sheep and replacing cattle with sheep were associated with declines in many upland birds that may be linked to availability of arthropod prey. At 18 and 30 mo, arthropod biomass was twice as great in non-grazed and sheep plus cattle treatments than in pastures grazed with sheep only (Dennis et al., 2008). Including cattle increased sward structural diversity and arthropod abundance, likely favoring bird populations over time. Similarly, in a review of spider populations in pastureland, greater variation or patchiness in sward height favored spiders (Bell et al., 2001). The authors cautioned against grazing by sheep at high stocking rates and recommended use of lower stocking rates and/or mixed grazing to create a mosaic of short and tall swards.

### DISTRIBUTION OF LIVESTOCK IN THE LANDSCAPE

There has been limited research (11 papers cited) on effects of livestock distribution in pastureland on wildlife, with most considering exclusion of livestock from waterways and construction of riparian buffers. Agriculture activities may contribute the largest amount of sediment to streams, primarily through row crop cultivation

in flood-prone areas and livestock grazing in riparian areas (Waters, 1995).

### Birds

In Florida breeding pairs of crested caracaras selected pastureland as home range more than forest, oak scrub, and marsh (Morrison and Humphrey, 2001). Compared with pairs nesting in natural areas, those nesting on land used for cattle ranching exhibited higher rates of breeding-area occupancy, attempted breeding during more years, initiated egg laying earlier, exhibited higher nesting success, and more often attempted a second brood after successfully fledging a first. Reasons for these responses are not clear nor are the effects of specific grazing practices, but the importance of pastureland habitat to reproduction of crested caracaras is well established.

In Portugal species richness of grassland wintering birds was determined primarily by the broader landscape context, and abundance was determined mostly by field management (Moreira et al., 2005). High species richness was associated with diverse landscapes, high stream density, and forest and shrub cover that act as sources of nonagricultural avian species to pastureland. Fields located in homogeneous, arable landscapes tended to be species poor though they had the highest abundance of seed-eating birds, particularly winter visitors.

In Wisconsin a variety of land uses including alfalfa hay field, dry pasture, and cool-season grass pasture were evaluated for grassland bird species richness. Structure and composition of the landscape and patch size were the most important factors to consider in affecting species richness and management for grassland birds (Sample et al., 2003).

### Reptiles and Amphibians

In Pennsylvania there was no effect due to exclusion of beef cattle from riparian areas for 1 to 2 yr on abundance, richness, or biomass of all reptile and amphibian species combined (Homyack and Giuliano, 2002). Northern queen snakes and eastern garter snakes were more abundant in riparian areas where cattle were excluded. The authors suggested that these reptiles and amphibians likely require > 4 yr to respond to changes in management due to reproductive potential, proximity to



Desirable site  
characteristics  
vary among  
avian species”



...pastureland is one component of a diverse landscape and not the sole source of wildlife habitat in a given region.”

nearest remnant population, and dispersal ability. Also, such areas likely did not have sufficient time for vegetation, water quality, and macroinvertebrate populations to recover, thus allowing herpetofauna to recolonize the sites. This underscores the need for longer-term studies to allow the ecosystem to equilibrate.

### **Invertebrates and Fish**

Stream physical habitat and fish communities were evaluated in Wisconsin during 13 yr (Wang et al., 2006). Only stream segments with riparian buffers protected by exclusion fencing showed major improvements in stream physical habitat. Improvements in fish community structure were not found for any of the implemented practices; however, annual measurements varied substantially, and this pointed to the need for long-term studies.

While examining macroinvertebrate communities in Pennsylvania streams with exclusion fencing and riparian restoration, Carline and Walsh (2007) found only modest improvements in community composition and structure. Treatments improved macroinvertebrate density in the stream, which was attributed to lower suspended sediment levels. Installation of exclusion fencing in Pennsylvania allowed channel revegetation and a 30% increase in total number of macroinvertebrates (Galeone, 2000). In Wisconsin continuous stocking reduced macroinvertebrate populations more than did rotational stocking, woody buffer strips, or grass buffer strips (Weigel et al., 2000).

### **Mammals**

In Wisconsin buffer strips led to increased species richness of small mammals and greater abundance (3–5 times) compared with managed intensive rotational stocking (Chapman and Ribic, 2002). Additionally, small mammal abundance was greatest within 5 m of the stream, regardless of the presence or absence of buffers, indicating the importance of stream-side zones as habitat. In southwestern Pennsylvania, small mammal species richness was 1.7 times greater and abundance was 2.2 times greater when livestock were excluded (Giuliano and Homyack, 2004). Results were attributed to 2.3 times greater litter cover and benefits from vertical vegetation obstruction.

In Spain the Iberian ibex is a wild goat that is endemic to the Iberian Peninsula and is a close relative of the domestic goat with similar feeding habits (Acevedo et al., 2007). The presence of the domestic goat caused the ibex to occupy a different habitat, often one that was suboptimal.

### **Summary and Recommendations: Livestock Distribution in the Landscape**

The literature indicates that pastureland grazed by livestock provides important habitat for wildlife species and that it is possible to manage pastureland for the benefit of both livestock and wildlife. It must be recognized, however, that pastureland is one component of a diverse landscape and not the sole source of wildlife habitat in a given region. Further, pasture species have different growth habits and are grazed differently by different herbivores. Thus, distribution of livestock throughout the diverse landscape can produce important niches for particular wildlife species (e.g., the crested caracaras in Florida) and the diversity of landscape features required by other species. Restricting livestock access to surface waters is justified by the current literature. Changes in water quality affect invertebrate populations relatively quickly, and buffer strips associated with livestock restriction result in relatively rapid increases in abundance and richness of small mammal populations. Restoring richness and abundance of reptiles, amphibians, and fish is a longer-term process that may require several years, but one that appears to be achievable.

## **OVERALL CONCLUSIONS AND RECOMMENDATIONS**

### **GRAZING INTENSITY Achieving Purposes of Prescribed Grazing through Managing Grazing Intensity**

The literature strongly supports the conclusion that grazing intensity is the prescribed grazing practice having the greatest impact on forage, animal, soil, water, and wildlife responses in pastureland. Grazing intensity affects forage mass and nutritive value and plays a major role in vigor and species composition/richness of plant communities. Increasing grazing intensity decreases forage mass on pastureland, and this is the primary determinant of the strong negative correlation between individual animal performance and grazing intensity. Increases

in grazing intensity have been linked to greater nutrient, sediment, and fecal coliform loading in water bodies, streambank erosion, and soil compaction resulting in decreased rainfall infiltration rates.

Evidence in the literature exists that increasing soil erosion, soil compaction, and declining soil quality are caused by excessive stocking rate. Avian species abundance and richness, nest site selection, and nesting success all have been negatively affected by high grazing intensity. The literature is equally clear, however, that the response to grazing intensity can vary widely for different wildlife species. Consequently, choice of grazing intensity must be evaluated considering the needs of livestock and the requirements of the broad array of wildlife species present in the ecosystem and not just those of a single high-profile species.

In conclusion, selecting the proper grazing intensity should be a primary focus in developing and carrying out management plans for agroecosystems in which livestock production, ecosystem health, and wildlife preservation are concurrent objectives. If conservation planning fails to identify, achieve, and maintain the proper grazing intensity, the secondary factors such as choice of stocking method, season of grazing and deferment, or any other prescribed grazing strategy will not be able to overcome this failure.

Further, when climatic or other conditions lead to deviation of ecosystem balance away from the defined goals, some form of adaptive management must be implemented to correct grazing intensity and other factors to allow the system to equilibrate. Thus, in addition to the skill in planning, designing, and implementing the prescribed grazing standard, educational programs are needed to assist the manager in recognizing changes and adjusting management strategies to achieve system goals. This would be aided by a process of periodic monitoring by NRCS to assist in evaluating the success of the practice and in identifying needs for adaptive management.

### Gaps in the Published Literature regarding Grazing Intensity

The general nature of the relationship between forage quantity and grazing intensity and that

between individual animal performance and grazing intensity has been well defined. Despite statements regarding the importance of grazing intensity as a controlling variable in ecosystem health, little research has been conducted in that area. Critical thresholds for grazing intensity, above which lead to occurrences of substantial environmental impacts, have not been established in the USA for pasturelands. This would be a valuable first step. Then the interactions among the predominant or desired forage, livestock, and wildlife species occupying the grassland need to be quantified. This will likely need modeling efforts.

A great need also exists for conducting comprehensive grazing intensity studies (measuring soil, water, air, wildlife, plant, and animal responses) in several locations within the humid USA. This work would best be done by well-funded and accomplished multidisciplinary teams of scientists at strategically selected and appropriately equipped regional centers. Team members need not all work at one location but could be brought together to develop experimental protocols for the project and to synthesize the data generated.

Once data are accumulated and evaluated, modeling approaches can assist in transferring the technology and expanding inference of responses to a wider range of ecosystems. This requires more education of the NRCS personnel and others to train producers, but it would help advisors predict and monitor the appropriate grazing strategies for a given site. Models could integrate site-specific information on crop and pasture systems to define, from a landscape perspective, the role of the pasture in providing ecosystem services, including water quality and habitat for wildlife. This approach would inform decision makers about the appropriate forage species and prescribed grazing practices needed to meet specific goals at the farm and the broader ecosystem level.

### STOCKING METHOD Achieving Purposes of Prescribed Grazing through Managing Stocking Method

The pastureland literature supports a conclusion that rotational stocking increases forage quantity-related responses relative to continuous



Critical thresholds for grazing intensity, above which lead to occurrences of substantial environmental impacts, have not been established...for pasturelands.”



...stocking method (is) an important prescribed grazing practice, but one that is secondary...to grazing intensity”

stocking. The effect of stocking method on forage nutritive value is inconclusive, and although the literature indicates that stocking method affects pasture botanical composition and persistence, interactions with other factors, especially grazing intensity, make it impossible to generalize about which stocking method is best across situations. The literature supports a conclusion that rest periods between grazing events provide greater flexibility in choice of grazing intensity. The literature also supports that grazed grasslands maintain greater plant species richness than non-grazed areas and that prescribed grazing is a key component in sustaining species diversity of grassland communities.

Daily animal production is generally not affected by stocking method, with an exception being when species composition of the pasture changes over time due to stocking method. The effect on gain per ha is less clear, but when differences occur, they generally favor rotational stocking. Conclusions from this pastureland review are in general agreement with those of Briske et al. (2008) for rangeland, with the exception that there appears to be greater likelihood of an advantage in pasturelands for higher gain per ha for rotationally stocking over continuous stocking than there is for rotationally stocked rangeland. This could be due to the plant species used, amount of inputs, differences in rainfall, and potential for greater plant growth.

The majority of studies on stocking method effects on water quality, hydrology, and stream morphology indicate that rotational stocking has less negative effect than continuous stocking. Accumulation of additional forage mass and ground cover during regrowth periods accounts for some of the benefits attributed to rotational stocking. In total, the literature supports stocking method as an important prescribed grazing practice, but one that is secondary in importance to grazing intensity.

### Gaps in the Published Literature regarding Stocking Method

Briske et al. (2008) concluded that “a continuation of costly grazing experiments adhering to conventional research protocols will yield little additional information.” However, based on the current literature

assessment for humid pastures, the most compelling justification for additional stocking method studies is to assess their impact on responses beyond pasture plants and domestic animals, specifically soil, water, and wildlife. The lack of information regarding the influence of stocking method on soil, water, and wildlife responses suggests need for such comparisons at strategically selected sites throughout the humid pastureland regions of the USA. Multidisciplinary teams of the best scientists nationally should be assembled to coordinate these studies, so that treatment selection and response measurements are done in a manner that will generate conclusive results and support potential modeling efforts. This work would serve as an authoritative guide to future prescribed grazing recommendations.

In agreement with Briske et al. (2008), more consistent or standardized research protocols are needed for stocking method comparisons of forage mass, accumulation, nutritive value, and species composition. Based on the preliminary data available, more measurements are needed on plant and soil factors that contribute to wildlife habitat and food sources. The studies need to be multidisciplinary and long term to capture responses along the way to ecosystem stabilization and for evaluating the treatments while at steady state.

### SEASON OF GRAZING AND DEFERMENT Achieving Purposes of Prescribed Grazing through Season of Grazing and Deferral

Stockpiling is the most common deferred stocking practice and is useful for extending the grazing season, reducing reliance on stored feed, and improving animal health and performance. Timing of initiation, termination, and deferral of grazing, along with inclusion of complementary cool- and warm-season forages in the production system are important prescribed grazing practices for maintaining forage cover and desired sward botanical composition.

Ground cover is critical because the largest negative effects on water quality typically occur when cover is compromised, particularly  $\text{NO}_3\text{-N}$  leaching and sediment loss. Highest runoff rates occur during dormant seasons

when evapotranspiration is lowest; thus winter feeding on grassland can impact water quality significantly.

Animals grazing on unstable or wet soil can increase soil bulk density and penetration resistance and decrease aggregation, all of which will negatively affect productivity and environmental quality. Research supports the removal of livestock from riparian areas during periods of high soil saturation.

Most wildlife studies relate to the effect of timing of grazing on vegetation characteristics at potential avian nesting sites or on nesting success. For many avian species, deferral of grazing is critical for nesting success. Incorporating additional pastureland species is a practice that provides variation in sward structure and differences in seasons of growth, making it relatively easy to vary the timing of grazing.

### Gaps in the Published Literature regarding Season of Grazing and Deferral

As need increases for high-quality forage in pastures, additional research into optimal timing of initiation, termination, and deferral of grazing will be critical. Relatively little of this work has been done in the USA. Effects of timing of initiation of grazing on subsequent forage production and nutritive value, and the effect of timing of termination on persistence and regrowth suggest that this is an area that would benefit from increased research.

There remains a need for comprehensive studies to understand the multitude of soil changes in response to season of grazing and deferral. For example, it is unclear whether season of grazing or deferral might affect long-term soil organic matter accumulation and how, in turn, this affects soil quality and forage and animal productivity. Questions

Excessive stocking rates can reduce herbage mass and vegetative cover and increase occurrence of soil erosion. Photo by Lynn Betts, USDA NRCS.





Distance to water is more important than paddock size with respect to optimizing grazing distribution and animal performance.”

remain regarding exclusion of livestock from riparian areas, including the level and timing of such disturbances and their effect on plant, mammalian, avian, and benthic species. Obtaining this knowledge would allow for improved management of pasturelands and their riparian areas to support livestock production while improving diversity and numbers of nonlivestock species.

### **TYPE AND CLASS OF LIVESTOCK** **Achieving Purposes of Prescribed** **Grazing through Type and Class of** **Livestock**

Within a livestock species, no evidence was found that breed or age has significant effects on pasture characteristics or ecosystem services. The literature supports a conclusion that co-grazing or grazing by particular species can be used effectively as a prescribed grazing tool to manipulate botanical composition of pastures and to decrease abundance of invasive, unwanted, or potentially toxic plants. Relative to animal health and production, the consensus of the literature is that choice of animal species is less critical than grazing intensity. Little comparative evidence exists in the humid USA to assess the effects of livestock type and class on soil erosion and condition. Only two papers were found that addressed the role of type and class of livestock on wildlife, and both focused on the impact of livestock species on sward structural diversity and arthropod abundance. Grazing by cattle or cattle plus sheep, instead of sheep alone, created greater variation or patchiness in sward height favoring spiders, an important food source of some birds.

### **Gaps in the Published Literature** **regarding Type and Class of Livestock**

Further research on plant response to grazing by type and class of livestock is needed because studies to date have been limited both geographically and in the forage species tested. The interaction between livestock species and stocking rate is not well understood in terms of plant and animal response, but especially on wildlife and soil and water responses, and is an important area for future research. Little research has assessed the effect of various livestock species on water quality, hydrology, riparian health, and watershed function. Research into the environmental responses

from differing grazing livestock is needed as age, physical characteristics, and grazing behavior vary among species. Particularly lacking is research on the effects of horses and sheep.

Better understanding of the effects of different types of livestock on the environment will help develop best management practices such as riparian buffers and refine grazing techniques to mitigate problems such as overgrazing. A great need exists to determine the differential effects of single-species, single-age, mixed-species, and mixed-age livestock effects on soil erosion and soil condition in the humid USA.

### **DISTRIBUTION OF LIVESTOCK IN** **THE LANDSCAPE** **Achieving Purposes of Prescribed** **Grazing through Distribution of** **Livestock in the Landscape**

Sloping areas often have shorter livestock grazing time and are associated with greater species richness and legume proportion, but lower rates of herbage accumulation than summit or toeslope areas. Shade has a greater impact on livestock distribution than does location of water source during warm seasons or in warm climates. Distance to water is more important than paddock size with respect to optimizing grazing distribution and animal performance. This suggests that increasing the number of shade and watering points in conjunction with decreasing paddock size minimizes spot grazing and reduces associated stand deterioration. From an animal health and production standpoint, key management factors include minimizing distance to water, increasing quality of drinking water by providing alternatives to surface water, and providing shade. These prescribed grazing practices should be considered as part of an overall management plan.

Distribution of livestock throughout the landscape can provide important niches for particular wildlife species and the diverse landscape features required by other species. The majority of the literature pertaining to livestock distribution effects on water and wildlife addresses exclusion fencing and riparian buffers. Restricting livestock access to surface waters is justified by the current literature

because changes in water quality occur quickly and affect wildlife populations. Livestock restriction from riparian areas has resulted in relatively rapid increases in abundance and richness of small mammal populations. Restoring richness and abundance of reptiles, amphibians, and fish is a longer-term process, but one that appears to be achievable.

### Gaps in the Published Literature regarding Distribution of Livestock in the Landscape

The literature describing plant and animal responses to livestock distribution is limited. Greater research efforts are also needed to understand the effects of livestock distribution management systems on shallow groundwater quality and recharge. Livestock distribution is a research area where scientists evaluating soil, water, and wildlife responses could collaborate more closely with pasture and animal scientists.

### Final Synopsis

The NRCS has developed conservation practice standards to provide guidance for applying conservation technology on the land and setting the minimum acceptable level for application of the technology. The goal of this literature synthesis was to determine if practices defined in the Prescribed Grazing Practice Standard (Code 528) meet the purposes and criteria that were established for their implementation. The assessment was organized around five purposes or desired outcomes that arise from imposing prescribed grazing. Prescribed grazing strategies evaluated include grazing intensity, stocking method, season of grazing and deferment from grazing, type and class of livestock, and livestock distribution on the landscape. Summation assessments were made of the literature support for each purpose and their criteria in Code 528 (Table 3.1).

Specific details regarding these strategies and their impacts on plant, livestock, water, soil, and wildlife were presented and summarized throughout this chapter. Prescribed grazing practices clearly have major influence on plant, livestock, water, soil, and wildlife. Proper grazing intensity is the most important prescribed grazing strategy on pastureland ecosystems, and conservation plans should

prioritize its implementation. Stocking method is useful for fine-tuning the overall production system once an appropriate grazing intensity is imposed. Choice of rotational over continuous stocking has been shown to positively affect forage accumulation rate and forage utilization efficiency on pastureland as well as important measures of water quality. Season of grazing affects forage ground cover, which in turn influences water infiltration, runoff into surface water bodies, and availability of wildlife habitat, avian nesting sites, and food supply for wildlife and livestock. The literature describing effects of type and class of livestock was limited primarily to studies of effects of mixed-species grazing on plant communities. Most literature on distribution of livestock in the landscape has assessed the effects of shade, water, and fence placement on components of the pastureland ecosystem.

Although societal interest and emphasis on soil, water, and wildlife is increasing, a paucity of literature addressing these ecosystem components is seen. This leads to a recommendation that future grazing studies on pastureland be more comprehensive in scope, including soil, water, and wildlife responses in addition to plant and livestock measures, and be carried out over longer time periods to allow the full impact of prescribed grazing to be quantified. These data would then provide the basis for development of effective pastureland ecosystem models.

Last, there appears to be a significant future role for emphases, including 1) use of prescribed grazing to correct undesirable trends in pastureland response and restore desired grassland condition, 2) better education of end users regarding implementation of prescribed grazing technology, 3) detailed monitoring and reporting of the impacts of implementation of prescribed grazing practices to more effectively use adaptive management to adjust the system to meet goals, and 4) quantifying effects and interactions to guiding future assessments of their merit.

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## CHAPTER

# 4

# Forage Harvest Management

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management to provide ecosystem benefits and the economic return can be complementary, but in many cases the desired outcomes are competitive.”

# Forage Harvest Management

C. Jerry Nelson, Daren D. Redfearn, and Jerry H. Cherney

## INTRODUCTION

The NRCS Conservation Practice Standard Code 511 (see Appendix I) addresses timely cutting and removal of forages from the field as hay, green-chop, or silage to optimize yield and quality of the product while maintaining stands for the desired length of time. In addition, there are implied and stated criteria for environmental and wildlife benefits, respectively. However, achieving these benefits may require altering management to accept some reduction of yield or quality to maintain or enhance abundance and diversity of wildlife, reduce soil erosion, and reduce contaminants such as fertilizer elements and pesticides from entering surface and groundwater. Code 511 contains a series of prescribed purposes and criteria or guides for achieving each purpose. A team of respected forage specialists was formed to determine the science base for the practice standard (Table 4.1).

The primary goal of the harvest manager is to obtain a good yield of a quality product that allows for stand persistence. Until recently economic returns to the land owner/client have been assumed to include the basic foundation for meeting conservation goals and providing other desired ecosystem services. In some cases the management to provide ecosystem benefits and the economic return can be complementary, but in many cases the desired outcomes are competitive.

This shows the need for literature assessments to determine what management changes would improve the provision of these long-term services with the least effect on economic value of the forage harvested. The literature assessment will also expose deficiencies in research information (Table 4.1).

The evaluation team recognizes that Conservation Practice Standards are written as the base for meeting national priorities, so by design they are broad and more general to form the foundation. The purposes and criteria are then adapted to state and even local conditions for planning, education, and implementation of practices. In that way, proposed use of the forage, species of forage harvested, soil resources, and local environmental and wildlife concerns need to be considered during implementation. In most cases, research is focused on basic principles that need to be interpreted to fit the situation on each specific landscape where the practice is being applied. States can utilize research to build on the national standard to address specific situations and needs. Further, local knowledge and experience of agency personnel are needed to fine-tune applications of the practice for specific sites and goals.

With the above broad perspective we considered the major forage species according to region of adaption. This mostly led to conclusions regarding tolerance to low and high temperatures and to drought stress, which primarily affect competitiveness and persistence. We then evaluated general plant growth habits that are desirable for one or more mechanical harvests during the growing season. Growth habits give insight to the yield potentials, forage quality, regrowth processes, and their potential effects on environmental concerns and wildlife. Thus, most of the assessment effort was focused on perennials and how management decisions would interact with environmental conservation. Management considerations included use of chemical fertilizers and manures, potentials for soil erosion, effects on water quality, and provision of habitat and food supplies for wildlife.



Chopping wilted forage for ensilage in Missouri. NRCS photo by Charlie Rahm.

**TABLE 4.1.** Purposes of the Forage Harvest Management Practice Standard and the criteria used for assessment. The degree of research support for the each criterion is given in the last column.

Purpose of the Practice Standard	Criteria used for assessing achievement of the purpose	Support by research
<b>Optimize yield and quality of forage at the desired levels</b>	Harvest at frequency and height to maintain a healthy plant community as recommended by State Extension Service	Strong support on major species, limited on minor species or forbs used in special situations
	Harvest forage at stage of maturity for desired quality and quantity	Strong support on major species to optimize yield and quality
	Delay harvest if prolonged or heavy precipitation is forecast that would damage the cut forage	Moderate, need comparative data on rate of yield and quality change due to weather or to later maturity
	Harvest silage/haylage crops within the optimum moisture range for the storage structure(s) being utilized	Strong support for haylage and silage crops over a range of moisture contents
	Use State Extension Service recommendations for optimum and how to determine moisture content	Strong support for optimum content, but methods for field measurement need research
	Treat direct cut hay crop silage (moisture content > 70%) with chemical preservatives or add dry feedstuffs	Generally supported, research is variable on consistency of results achieved; cost effectiveness needs more research
	Invert swaths when moisture content is above 40% and rake hay at 30–40% moisture to maintain hay quality	Inverting assists the drying process, but leaf loss on some species can be high, need research on different methods and cost effectiveness
	Bale field-cured hay at 15–20% moisture; bale at 20–35% moisture if it is to be dried by forced air	Strong support, but need more research on quality losses from field drying vs. costs for water transport and costs for forced-air drying
	Chop ensilage to a size appropriate for the storage structure that allows adequate packing	Strong support for packing to exclude oxygen and maintain anaerobic conditions
<b>Manage for desired species composition</b>	Harvest at the proper height and frequency to maintain desired species composition	Strong research on height and frequency of cut can affect in short term, would be useful for use as an adaptive management method
	Fertilize with appropriate minerals at the correct time in the growing season	Strong support for use of N, P, and K and timing during the season to alter the botanical composition
<b>Use forage plant biomass as a soil nutrient uptake tool</b>	Use a harvest regime that utilizes the maximum amount of available or targeted nutrients	Moderate support for use of forages to utilize excess nutrients in cropping systems
	When desired, select species that can maximize nutrient uptake	Variation in nutrient uptake among species is known, but balance is more critical than uptake of a single nutrient
	Use proper balance of nutrients such as nitrogen to avoid toxic plant material for animals	Strong research support on NO <sub>3</sub> and HCN challenges in grasses, some research on N effects on alkaloids in some cool-season grasses

TABLE 4.1. continued.

Purpose of the Practice Standard	Criteria used for assessing achievement of the purpose	Support by research
Control insects, diseases, and weeds	Select harvest periods to control disease, insect, and weed infestations	Minimal research support except for insects on alfalfa (weevils and potato leafhoppers)
	Evaluate pest management options by planning conservation practice standard Pest Management (595)	Strong IPM research for alfalfa insects, but weak for other species, need research on loss economics
	Lessen incidence of disease, insect damage, and weed infestation by managing for desirable plant vigor	Strong support for maintaining plant vigor and high competition to reduce biotic challenges
Maintain or improve wildlife habitat	If suitable habitat is desired for wildlife species, appropriate harvest schedules(s), cover patterns, and plant height should be maintained to provide suitable habitat	Good support for delayed harvest of first cut for ground nesters and leaving stubble for winter cover and food source; most data on birds; raise cut height for some turtles
	Avoid harvest and other disturbances during nesting, fawning, and other critical times	Some research indicates biomass crops will be harvested late and will provide habitat in summer and winter for some forms of wildlife

Finally, we considered the purposes and criteria of standard Code 511 in terms of potential trade-offs in management to provide desired conservation and ecosystem services to the landowner and the public. Published US research literature was emphasized, but in some cases extension publications were used if based on literature and professional experience. In general, extension publications were based on sound scientific principles that were interpreted and adapted for state and regional conditions. This was expected since management research for local conditions is rarely published in national journals unless there is a unique feature that has regional or national application. Assessments of literature support for purposes and criteria of Code 511 were summarized (Table 4.1).

## REGIONAL ADAPTATION OF FORAGE PLANTS

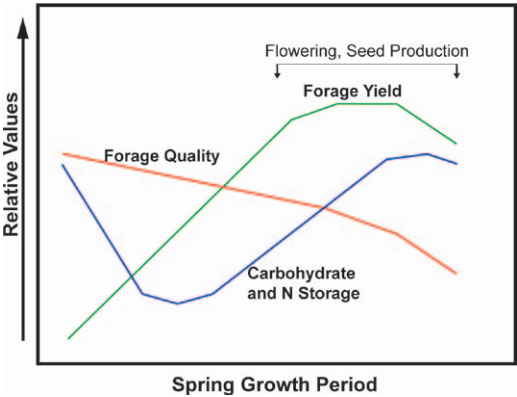
Scores of annual, biennial and perennial species are used as forages in humid areas of the eastern USA (Barker et al., Chapter 2, this volume). Some species are native, but most are introduced, and many of those introduced have become naturalized because of their long-term use (West and Nelson, 2003). Our assessments are also affected by regions due to increases in precipitation from the west, near the 100th

meridian, eastward to the Atlantic Ocean, and to increases in average temperature and length of the growing season going from the Canadian border to the Gulf of Mexico. These climatic variations form a matrix of temperature and precipitation that affect the forage species grown (see Figs. 1.1 and 1.2, Chapter 1, this volume), the number of times it is harvested, and the dominant livestock enterprises of the region that use the forage (Allen et al., 2007). Pest, pathogen, and wildlife populations also differ among regions to give an array of variables that affect adaptation of each forage species and its optimum harvest management for economic return and conservation.

Species differ in morphology and forage quality that help define their management use for growing or milking livestock in defined geographic areas of adaptation (see Fig. 1.1; Baron and Belanger, 2007). Nearly all State Agricultural Experiment Stations conduct extensive applied research to determine the major species and mixtures that are best adapted to the specific climate and meet yield, quality, and persistence needs for major livestock enterprises of the state. Yield, quality, and stand longevity are emphasized to determine the optimal harvest management regimes for economic return. These recommendations may include more specific

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Fortunately most states define optimum harvest times of forage crops according to growth stages based on flowering”



**FIGURE 4.1.** Relative changes in forage yield, forage quality, and content of carbohydrate and nitrogen reserves during the spring growth period. Data are generalized from several sources for legumes and the spring growth of most grasses.

management systems when the primary goal is yield, quality, or stand persistence. Cultivars within a species differ in maturity, seasonality of growth, yield potential, and quality of forage produced, thereby allowing some fine-tuning of management on a within-species basis for specific sites.

Fortunately most states define optimum harvest times of forage crops according to growth stages based on flowering of a monoculture or flowering of the most desired species in a mixture. This allows neighboring states to share performance data based on plant development such that recommendations for harvest management tend to have some similarity and transferability within geographic regions. Unfortunately there is little research on minor-use species or the latest “hot introduction,” which can lead to management decisions based on unreliable information, often based on promotional hype and testimonials. Eventually these factors are evaluated scientifically and documented in the literature, but by then there may be another generation of “wonder grasses” that needs scientific evaluation.

### GROWTH HABIT AFFECTS YIELD AND QUALITY

Since there are many species to consider they were divided into groups based on adaptation to climatic regions and then to morphological features that favor mechanical harvests for conservation as hay, silage, or biomass.

Legumes like alfalfa (scientific names for all species mentioned are given in Appendix III), red clover, and upright-growing types of birdsfoot trefoil have erect stems and regrow from the plant base, that is, the crown that exists at the top of the root near soil level (Beuselinck et al., 1994; McGraw and Nelson, 2003). In general, these characters, especially upright growth, provide adaptation to repeated but infrequent harvest for hay or silage through the season. In contrast, low, prostrate growing legumes such as white clover and prostrate birdsfoot trefoil retain leaf area near the soil surface and are usually better adapted to pastures where plants may not have long rest periods between defoliations.

During spring growth the yield of a grass or legume gradually increases and quality decreases through the flowering stage (Buxton and Casler, 1993; Nelson and Moser, 1994), after which plant parts senesce and yield gradually decreases while the forage quality decreases more rapidly (Fig. 4.1). Upright growing legumes also differ in time to maturity; e.g., alfalfa reaches the desired cutting stage earlier than red clover, which is earlier than upright birdsfoot trefoil. This range of maturity among species allows staggered harvest times, which also affect growth of associated plant species and provision of environmental services and biodiversity.

Upright growing legumes have morphological development during each regrowth similar to that during spring growth. Thus, in general, early spring harvest and shorter durations between subsequent harvests reduce yield but increase forage quality (Kallenbach et al., 2002). The actual relationships between increase in yield and decrease in quality of alfalfa differ for each harvest depending on environmental factors (Brink et al., 2010). In Pennsylvania and Wisconsin the daily rate of decrease in alfalfa quality was greater during the spring growth and first regrowth periods than during later regrowths. Thus, in the eastern USA the timing of harvest for alfalfa and other legumes is most sensitive during the early growth periods of the growing season.

Summer annual legumes including common lespedeza and soybean are also used in hayfields (Sollenberger and Collins, 2003). In southern

latitudes summer annual legumes such as smooth-seeded wild bean (Butler and Muir, 2010), and soybean, cowpea and pigeon pea (Foster et al., 2009; Rao and Northup, 2009) show potential. In the south, winter annual legumes can be planted into warm-season perennial grasses in autumn to extend the grazing season or to be harvested for hay in spring (Muir et al., 2007; Hancock et al., 2011). The legumes provide environmental and ecosystem value by providing winter cover and fixing atmospheric nitrogen. Some produce a seed bank for reseeding (Muir et al., 2005) and food for wildlife.

Legumes such as sweetclover and some other forbs are biennials that germinate in spring, grow through the summer, and overwinter to produce spring growth that can be harvested. Most will produce some regrowth after cutting then die. Nonlegume forbs in hayfields are usually managed as opportunists and are beneficial to wildlife, but often are low yielding and not valued highly for preserved forage. More assessments are needed on the overall benefits from these forbs.

Perennial grasses differ markedly in growth responses to temperature and are usually divided into cool-season and warm-season

species based on their photosynthetic system and optimum temperatures for growth (Table 4.2; MacAdam and Nelson, 2003). Photosynthetic rates of warm-season grasses are as much as 50% higher than cool-season grasses, and this is reflected in faster growth rates, especially at high temperatures. All legumes have a photosynthetic system that is similar to cool-season grasses, but they exhibit greater concentrations of protein and most minerals. Many legumes, such as red clover, have temperature optima similar to cool-season grasses, but others, such as alfalfa, perennial peanut and lespedezas, have growth temperature optima that are intermediate between cool- and warm-season grasses.

Similar to legumes, most cool-season grasses harvested for hay or silage, like orchardgrass, tall fescue, smooth brome grass, reed canarygrass and timothy, are upright growing and adapted to repeated but not frequent mechanical harvests. Except for timothy these grasses flower only one time in spring with optimum trade-off between forage yield and quality occurring between inflorescence emergence and anthesis (Fig. 4.1). Also, optimum dates differ among species to allow spread of harvest dates; for example, orchardgrass is several days earlier in maturity than is tall fescue, followed in order



All legumes have a photosynthetic system that is similar to cool-season grasses, but they exhibit greater concentrations of protein and most minerals.”

**TABLE 4.2.** Perennial grasses can be classified as warm-season or cool-season based on their photosynthetic process. The  $C_4$  photosynthetic system is more efficient in light use than the  $C_3$  system and is associated with high production and other characteristics. Adapted from several sources.

	Cool season	Warm season
Photosynthetic process, first product	$C_3$	$C_4$
Photosynthetic rate, $g\ CO_2\ m^{-2}\ leaf\ area\ h^{-1}$	2.0–3.0	>3.5
Light saturation, % of full sun	50–60%	>100%
N content of young leaves, % of dry wt	2.5–4.0%	1.5–2.5%
Water use efficiency, $g\ dry\ wt\ g\ water\ used^{-1}$	Low	High
Optimum temperature range, $^{\circ}C$	18–27 $^{\circ}C$	30–40 $^{\circ}C$
Daily growth rate, $kg\ day^{-1}$	Medium	High
Major representative species	Smooth brome grass	Bahiagrass
	Kentucky bluegrass	Bermudagrass
	Orchardgrass	Big bluestem
	Reed canarygrass	Caucasian bluestem
	Tall fescue	Indiangrass
	Timothy	Switchgrass



Switchgrass, big bluestem, and indiangrass are tall, upright growing grasses that are the main native warm-season perennials suitable for conserving forage as hay.”

by perennial ryegrass, smooth brome grass, and timothy (Balasko and Nelson, 2003). Further, late cultivars within a species matured 4, 8, 9, and 14 d later than did early cultivars for tall fescue, orchardgrass, timothy, and ryegrass, respectively (Hall et al., 2009), providing another way to obtain a range of first harvest dates.

Regrowths of most cool-season grasses consist mainly of leaves causing forage quality to decline at a slow rate (Brink et al., 2010). Hay made from leafy regrowth of grasses, especially orchardgrass, is prized for certain niche uses such as for young dairy calves, horses, and perhaps sheep, in part because it dries rapidly, is unlikely to mold if managed properly, and is very soft in texture. In most cases, however, the leafy regrowths of grass stands are grazed instead of being harvested mechanically.

Switchgrass, big bluestem, and indiangrass are tall, upright growing grasses that are the main native warm-season perennials suitable for conserving forage as hay. Optimum time of harvest for these grasses is later in the season than cool-season species in the same area, which again allows spread in harvest dates. Switchgrass is generally 4 or more wk earlier in maturity than big bluestem (Fig. 4.2), which is 2 to 3 wk earlier than indiangrass. These upright growing warm-season grasses, including some old world bluestems, have stiff stems that provide good habitat for wildlife, even during winter, and serve well as grass barriers for riparian areas (Karlen et al., 2007). These warm-season grasses are better adapted to drought and cold winters and grow much taller than bermudagrass, bahiagrass, or caucasian bluestem. The latter three grasses are introduced warm-season perennials that exhibit considerable prostrate growth and can be grazed or cut and preserved as hay. Napiergrass is a tall, upright warm-season grass that is adapted to subtropical areas.

Summer annuals (e.g., oat, corn, and pearl millet) or winter annuals (e.g., wheat, rye, or triticale) can be harvested for forage (Moser and Nelson, 2003). Annual grain crops decrease in forage quality as they grow until flowering but, in contrast to perennial forage grasses, may increase again in quality as the grain develops. True annuals are usually harvested

only one time, near anthesis, because of poor regrowth. Forage sorghums are perennials that have some regrowth after cutting, but they lack cold hardiness and are managed like annuals throughout most of the USA. Annual forages were not reviewed in detail for our analysis of conservation benefits because many of the environmental and ecosystem relationships are similar to those resulting from grain harvest (Schnepf and Cox, 2006).

In summary, forage stands for hay or silage harvest consist mainly of upright growing plants with emphasis on the first cuttings, which have the highest potential for yield and quality. The yield of regrowths is usually lower and has a slower rate of decrease in quality, and the forage value is less sensitive to timing of harvest. Thus, most landowners are less flexible for adopting conservation practices that would lower economic return during the first harvest compared with later harvests. Unfortunately, most water management and erosion challenges from short stubble occur during the high rainfall period that also coincides with the dominant time of bird nesting and fledgling. As described there are alternative species that match with earlier or later harvests. And height of cut will also affect the amount of vegetation remaining for water management and certain wildlife. These details are considered in the analysis.

## HARVEST MANAGEMENT FOR STAND PERSISTENCE

Delayed harvest usually allows more carbohydrate and nitrogen storage in roots of upright-growing legumes or in the lower plant parts of grasses, which can be used to support regrowth vigor and persistence (MacAdam and Nelson, 2003). Vigorous plants are more competitive with weeds and other species resulting in better plant persistence, especially the proportion of desirable legume plants within mixed swards. Depending on livestock requirements, or for nonlivestock purposes, harvest management requires compromises to produce the largest quantity of a quality product for the desired number of years.

Strategies for plant persistence of perennial legumes are based on whether they are crown formers using a single taproot (e.g., alfalfa)

**TABLE 4.3.** Legumes differ in their persistence strategies depending on whether they are crown formers that retain the original root or if they are clone formers that spread laterally by stolons or rhizomes and take root. Annuals, biennials, and short-lived perennials must reseed naturally or have seed applied at a regular interval. Adapted from Beuselinck et al. (1994).

Species name	Persistence strategy			Life cycle		
	Crown former	Clone former	Reseeder	Annual	Perennial	Biennial
Alfalfa	X				X	
Arrowleaf clover			X	X		
Barrel medic			X	X		
Berseem clover			X	X		
Big trefoil	X		X		X	
Birdsfoot trefoil	X		X		X	
Black medic			X	X		
Burr medic			X	X		
Cicer milkvetch	X	X			X	
Common lespedeza			X	X		
Crimson clover			X	X		
Crownvetch		X			X	
Hairy vetch			X	X		
Korean lespedeza			X	X		
Kura clover		X			X	
Leucaena	X				X	
Persian clover			X	X		
Red clover	X		X		X	
Rose clover			X	X		
Sanfoin	X				X	
Sericea lespedeza	X		X		X	
Subterranean clover			X	X		
Sweetclover (white)	X		X			X
Sweetclover (yellow)	X		X			X
White clover		X	X		X	

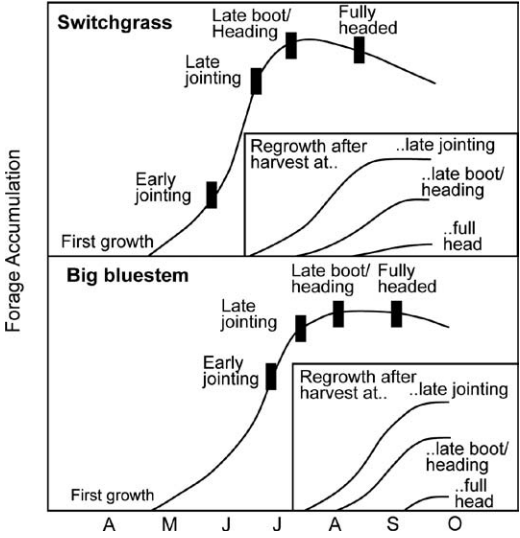
or clone formers that can form new plants by spreading laterally using stolons (e.g., white clover) or rhizomes (e.g., crown vetch; see Table 4.3). Crown formers depend on longevity of individual plants and rarely reseed (Fig. 4.3). Clone formers must have a low canopy density at certain times to allow light penetration to stimulate shoot development from stolons and rhizomes, but this also allows annual weeds to invade. In addition, canopy density has to be extensive enough during

summer to shade the soil to maintain low soil temperatures and restrict germination and development of annual weeds.

Plant persistence of alfalfa in Missouri was reduced by frequent harvest since plants were weakened and died allowing weeds to invade the stand (Kallenbach et al., 2002). There was little difference in persistence among cultivars. In Kentucky new alfalfa cultivars differed only slightly in yield and persistence under a

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Most managers want to reduce risk of winter kill of legumes, which can result in complete loss of a stand.”



**FIGURE 4.2.** Switchgrass in Nebraska goes through various growth stages earlier in the season than does big bluestem. Harvest at earlier stages of maturity of both species increases duration and amount of regrowth. Adapted from Mitchell et al. (1994).

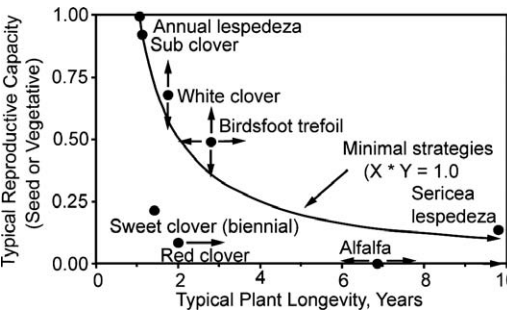
range of harvest frequencies, but all cultivars were best when cut at early bloom and 35-d intervals compared to intervals of 25, 30, or 40 d (Probst and Smith, 2011). Lodging occurred more frequently at the 40-d interval. Many dairy farmers elect to harvest alfalfa more frequently, before blooms appear, knowing stand life will be reduced which is compatible when grown in rotation with row crops.

Most managers want to reduce risk of winter kill of legumes, which can result in complete loss of a stand. Thus, management strategies have been researched to ensure the plants in northern areas have 4 to 6 wk of growth in autumn to become winter hardy (Volenc and Nelson, 2003). In most areas it is critical to provide a canopy through winter to reduce soil freezing and thawing that causes heaving and death of plants (Fig. 4.4). Research in Missouri indicates alfalfa yield in late fall is low and rarely economic to harvest, even when plants are cut infrequently during the season (Kallenbach et al., 2005). In southern areas perennial legume plants are managed carefully during summer to ensure the plants are not cut or grazed too closely. High soil temperatures can weaken plants to be less competitive with weeds and less tolerant of

insect damage and diseases. Perennial grasses are less sensitive to fall management than are upright legumes.

Reseeding is not common with upright-growing legumes because plants are harvested before seed development occurs with the result that stand persistence depends mainly on individual plant persistence (Fig. 4.3). If encouraged to reseed naturally, harvest must be delayed to allow seed to be produced, dropped to the soil, have adequate seed-soil contact, and be able to germinate at the proper time. When germinated, the seedlings need to emerge with minimal competition from species already present, whether they are desirable or weedlike (Barker et al., Chapter 2, this volume). Alfalfa plants are unique in that autotoxic compounds released to the soil inhibit germination and root growth of alfalfa seedlings for 6 mo or more (Jennings and Nelson, 2002).

Stand persistence of annual legumes like striate lespedeza (Davis et al., 1994) or several winter annual legumes (Muir et al., 2005) depend on natural reseeding. Needs for reseeding also occur with biennials and short-lived perennials like red clover and birdsfoot trefoil that succumb to diseases (Beuselinck et al., 1994). Plants need to be managed to produce seed naturally, which works for birdsfoot trefoil and lespedeza (Redfearn and



**FIGURE 4.3.** Annual legumes maintain the stand by reseeding themselves whereas long-lived perennials maintain the stand by plant longevity. Perennial plants differ in their reproductive capacity from seed or vegetative spread to form new plants. The solid line ( $X \times Y = 1.0$ ) is the minimal capacity from each process needed to maintain the stand indefinitely. Arrows associated with each data point indicate how management can alter the longevity or reproductive capacity. Adapted from Beuselinck et al. (1994).



Nelson, 2003). Red clover is well known for its good seedling vigor (Gist and Mott, 1958), but managing for seed production and natural reseeding has not been consistently reliable. Instead it is reseeded regularly, usually in late winter, and the existing canopy needs to be controlled (Barker et al., Chapter 2, this volume). In addition, proper fertilization regimes are critical to stimulate vigor of seedlings and not the competing canopy.

Aside from crabgrass, few annual forage grasses are used for hay or silage, and there are no important biennial grasses, so emphasis is usually on perennials. Perennial grasses also can be classified as bunch formers or sod formers. Bunch formers such as big bluestem and orchardgrass are somewhat similar to crown-forming legumes in that the lateral buds near the soil level develop into upright tillers that contribute limited lateral growth (Moser and Nelson, 2003). This usually leaves open areas of soil between plants. Other grasses

such as smooth brome grass, reed canarygrass, bahiagrass, and bermudagrass are sod formers that spread by lateral tillers, rhizomes, or stolons to fill in open spaces. Compared with upright bunch grasses, sod formers have smaller tillers, thinner stems, more leaf area near the soil surface, and are more tolerant of frequent cutting to short stubble heights. Tall fescue produces short rhizomes and is flexible; it is bunchy when cut infrequently and sod forming when cut or grazed frequently.

Grass plants cut during reproductive growth of the first harvest depend on carbohydrate and nitrogen reserves stored in the plant for vigorous regrowth (Fig. 4.1). Vegetative regrowths of cool-season grasses during summer and fall depend largely on photosynthesis from residual leaf area. As described above, associated legumes tend to repeat the canopy shape and flower in each growth period, whereas the dramatic shift in grass morphology changes the competitiveness

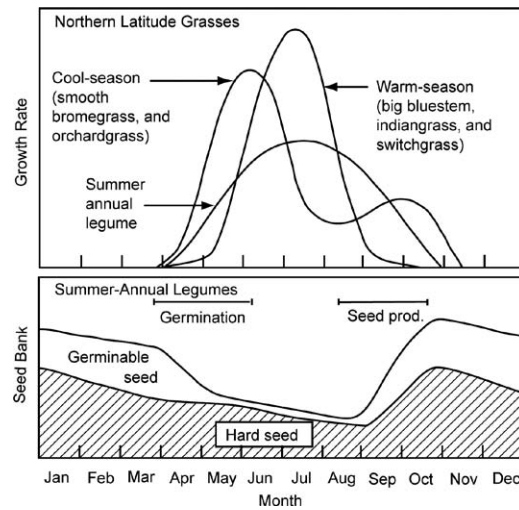
Grassland specialist discusses pasture condition with farmer in Missouri. NRCS photo by Charlie Rahm.

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Some managers emphasize grazing as the preferred harvest method but still use a single mechanical harvest for hay or silage as a tool to prepare hayfields or pasture areas for grazing.”



**FIGURE 4.4.** Alfalfa plants lifted from the soil by freezing and thawing of the surface soil in Iowa. The root is broken, and the plants will be weak and die. Photo courtesy of Steve Barnhart.



**FIGURE 4.5.** Annual growth curves for perennial cool-season grasses (top) and annual warm-season legumes (bottom). Cool-season grasses have reproductive growth during spring followed by vegetative growth for the rest of the year. Summer-annual legumes germinate in spring when competition is low and produce seed in autumn.

of the canopy. This difference in canopy structure during regrowths needs to be understood to effectively manage fertilization and cutting management of forage mixtures to maintain desired proportions of grasses and legumes (Fig. 4.5). In contrast with cool-season grasses, introduced warm-season perennial grasses (e.g., bermudagrass and bahiagrass) tend to flower repeatedly during summer, so production is not as cyclical (Fig. 4.6). The grasses regrow from buds that are supported by current photosynthesis of residual leaf area and some carbohydrate stored in stem bases.

## REASONS FOR FORAGE HARVEST

Some managers emphasize grazing as the preferred harvest method but still use a single mechanical harvest for hay or silage as a tool to prepare hay fields or pasture areas for grazing. In this case, timing of the single harvest, being early or late, and proper height of cutting are based on stimulating vigorous regrowth for pasture. Seed harvest of cool-season grasses is another option that occurs very late when stems are mature and provides nonforage income and prepares the stand for grazing. In this case, residual herbage after seed harvest that consists of basal parts of stems and old leaves should be harvested, packaged, and stored as low-quality forage. Removing residue after seed harvest opens the canopy to stimulate new tillers and regrowth, which shortens the time needed before leafy regrowth can be grazed later during summer or accumulated for autumn or winter grazing (Sollenberger et al., Chapter 3, this volume).

Since the spring growth period is usually the most productive, especially with cool-season grasses, it is the most desired stage for hay or silage production. Under these circumstances, other animals are needed or selected pastures of the forage area on a farm may be harvested once while other areas are grazed during spring. Then, during summer and fall when growth is slower, the entire area is grazed, either continuously or rotationally (Sollenberger et al., Chapter 3, this volume). This allows the manager to “rotate” the areas cut for hay or silage such that any one area is mechanically harvested about 1 yr in 3. Fertilizer timing and allowing plants to grow to near maturity for mechanical harvest are adaptive management practices that can revitalize the stand by reducing weed problems, altering insect cycles, reducing disease pressures, and restoring a better balance of legumes and grasses in the mixture. It may also be more wildlife friendly.

## SUMMARY

The Practice Code requires conservation practices be a part of the total management strategy for hay and silage crops. Most conservation practices include reducing soil erosion, maintaining water quality of runoff or flow through, and providing wildlife food

supplies and habitat that all depend largely on maintaining groundcover. Achieving the multiple objectives of yield, quality, and species composition while controlling insects, diseases, and weeds, being an effective nutrient uptake tool, and maintaining or improving wildlife habitat will require compromises in management. How that is achieved will depend on balancing priorities and incentives.

As pointed out above, most forage species used for hay or silage are upright growing grasses and legumes that can be grown in monoculture, especially alfalfa, or in legume-grass mixtures. For the latter the maturities need to be matched so components are compatible when harvested at appropriate times. Harvest management and species selection also affect winter ground cover, rate of regrowth after harvest to reestablish adequate ground cover, appropriate cutting heights, and optimal timing of fertilizer or manure applications. Fortunately there is flexibility among options like species selection, harvest stages, cutting heights, cutting frequency, and potentials for providing ground cover throughout the year. The literature review is focused on achieving the multiple purposes and criteria described in the Conservation Practice Code 511 (Table 4.1).

## THE CEAP ASSESSMENT OF FORAGE HARVEST MANAGEMENT

To determine if prescribed practices are effective in meeting the purposes, a series of questions were framed to focus on each purpose (Table 4.1). Then US scientific literature, especially peer-reviewed literature, was reviewed to determine if the practice, in fact, did provide the production goals, desired ecosystem services, or both. As discussed above, general principles of harvest management have been researched by scientists at Agricultural Experiment Stations within each state to know when forages can be harvested to obtain maximum economic return to the producer. But the standard also has primary challenges of evaluating if and how forages could be managed more flexibly to obtain forage yield and quality at some acceptable level, while promoting vigorous plant regrowth, maintaining stand life, and providing desired ecosystem services.

Special attention was given to whether the prescribed practice maintains desired species composition over time, whether biomass produced is effective in soil nutrient uptake, and if management can be flexible enough to help control insects, diseases, and weeds while maintaining and/or improving the environment and biodiversity of wildlife. This approach by purposes helped organize the assessment for each criterion, after which an overall assessment of research support was made and deficiencies noted in Table 4.1.

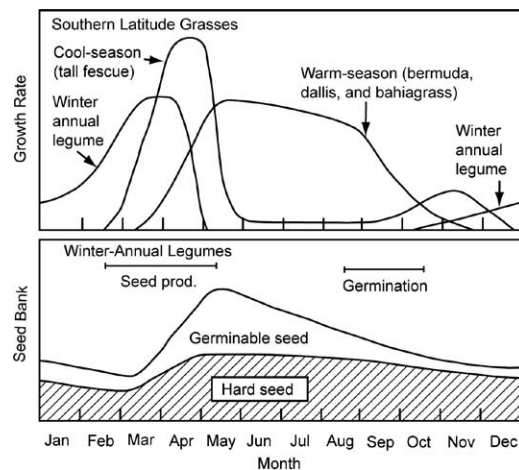
## PURPOSE 1: OPTIMIZE YIELD AND QUALITY AT DESIRED LEVELS

With increasing costs of concentrate feed supplements there is more emphasis on high protein and generally higher quality forage to help offset concentrate use for dairy and beef production. This emphasis can affect species selection, as well as harvest time and frequency. Mixed grass-legume stands are more likely to provide higher quality forage than pure grass stands (Merry et al., 2000). Increased desire for higher quality forage often results in harvesting more frequently, which may reduce stand life and potential benefits for wildlife.

### Harvest Time and Frequency

Land-grant universities and other agencies in the eastern USA have done a good job of

“desire for higher quality forage often results in harvesting more frequently, which may reduce stand life and potential benefits for wildlife.”



**FIGURE 4.6.** Warm-season grasses like bermudagrass have an extended period of high production that slows as days get shorter and cooler in autumn. Winter annual legumes provide additional forage and N fixation. Adapted from Bueselinck et al. (1994).



Overall, State Experiment Stations and Cooperative Extension Services have effectively provided adaptation and sound management recommendations for the major species and cultivars grown in their area.”

researching harvest management for major species grown in various geographic areas. Emphasis, however, has usually been on monocultures or legume-grass mixtures with goals of optimizing economic return to the producer in terms of yield, quality, and stand persistence. For example, recommended management of alfalfa for North Dakota focuses on winter hardy cultivars and good fall cutting management to allow development of winter hardiness. Cultivars with high winter dormancy (Group 2) are recommended, and stands are harvested two or three times at early bloom stages before 25 August (Meyer and Helm, 1994). Yields are similar, but quality is higher with three cuts. Another cutting can be made after plants stop growing in October, but strips should be left uncut to catch snow for insulation to reduce winter kill.

In Iowa, with a longer growing season and less severe winters, moderately dormant cultivars of alfalfa (Group 4) are recommended. They can be cut four times at early flowering with the last cutting by 1 September (Smith, 2008). Winter damage was increased when final cutting was delayed from mid-September to mid-October, and yield of first cutting the following year was reduced by 1.4 Mg ha<sup>-1</sup>. Removing late growth (cut 5) is cautioned on poorly drained soils since the standing regrowth provides insulation against cold and reduces freezing and thawing of the surface soil that may lead to frost heaving of plants (Fig. 4.4). In Kentucky, Group 5 alfalfa is adapted, and the crop is cut five times at early bloom. A late harvest or a late fall grazing is acceptable after growth has stopped. With milder winters the importance of fall management is lessened.

In general first cutting of alfalfa should be made at early bloom stage, but high temperatures are known to hasten maturity and flowering, so intervals between harvests are longer at northern locations. All states recommend cultivars with appropriate winter dormancy rating and prescribe P and K applications to improve persistence and yield. There is more emphasis on insects and diseases at southern locations. In all cases, management recommendations are based on the same basic principles that have been adapted for the environment, soil conditions, and length of growing season using local research.

These basic observations on management changes based on latitude are consistent for all major species of legumes and grasses. In general, plant adaptation principles can be transferred longitudinally more easily than across latitudes. Thus, similar to hardiness groups of alfalfa, different ecotypes of most perennial grasses have become naturalized over time for specific latitudes, especially native warm-season grasses. Cultivar differences within species of cool-season grasses allow adaptation across broader latitudes than do cultivar differences for many legumes (Baron and Belanger, 2007; Hall et al., 2009). Alfalfa is a marked exception since cultivar differences in fall dormancy and winter hardiness allow adaption in nearly all areas of the USA from California to Maine and from Florida to Alaska.

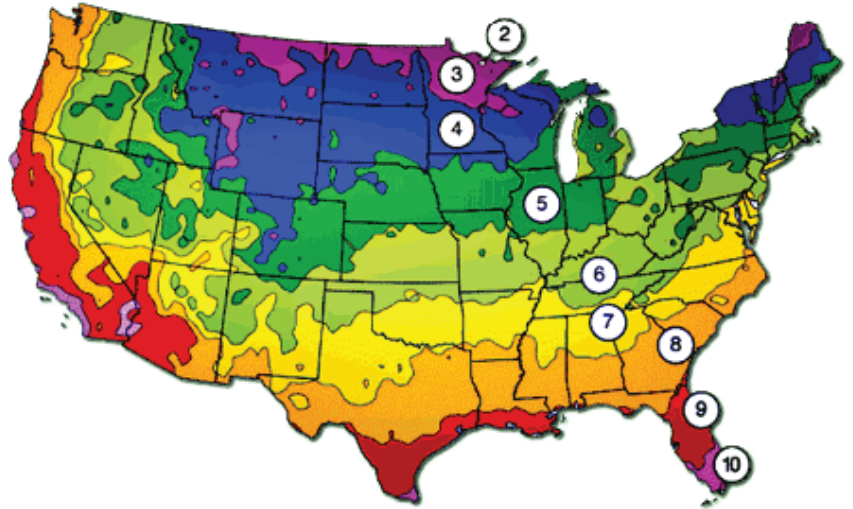
Loosely defined areas of geographic adaptation hold for other legume and grass species (Barnes et al., 2003; Hannaway et al., 2005). Good data are available for most species showing forage quality at harvest is inversely related to growing temperature. High temperatures are associated with lower concentrations of easily digested sugars in leaves and stems, a shift toward more cell wall and lignin formation, and a tendency to have smaller and shorter leaf blades (Buxton and Casler, 1993; Nelson and Moser, 1994). Thus, on average, quality of forage at the same growth stage is higher in northern locations than in southern locations (Matches et al., 1970). There is considerable indirect evidence that plant persistence is related more closely to winter temperatures in the north and to disease and weed pressures in the south. Overall, State Experiment Stations and Cooperative Extension Services have effectively provided adaptation and sound management recommendations for the major species and cultivars grown in their area.

A major contribution of USDA-ARS to geographic adaptation has been the revised Plant Hardiness Map (Fig. 4.7) that is based on average minimum winter temperature and is interactive with GPS and other tools to assist in determining adaptation of species to geographic areas. The revised map has a stronger base than the 1990 version, and zone boundaries in the map have shifted in many areas. The new map is generally one half-zone warmer than the previous map throughout much of the USA, as a result of a longer and more recent averaging

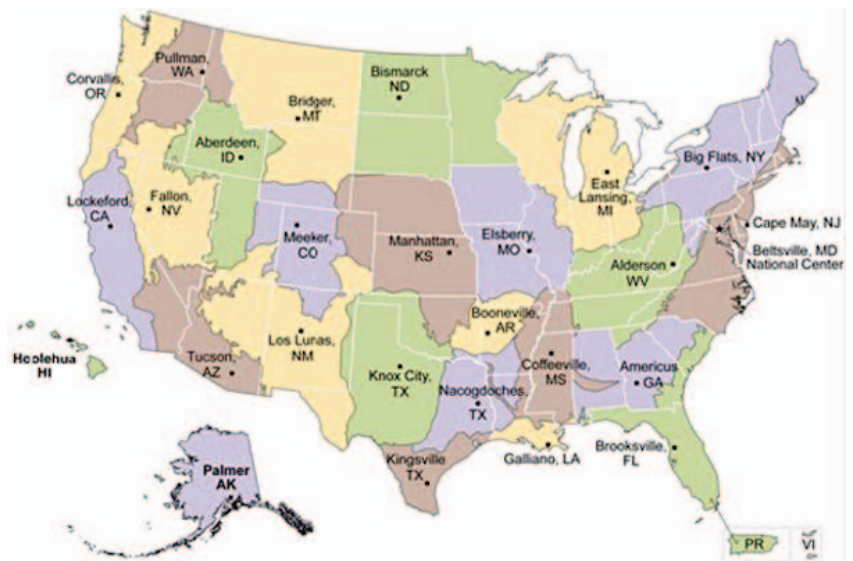
period (1976–2005). Some changes in zones are due to use of new, more sophisticated mapping methods and a greater number of observation stations. Thus, the revised map has greatly improved accuracy, especially in mountainous regions. Because of the way the map is constructed, using data for only 30 yr, it is not an indicator of global change which requires longer durations. Nevertheless, it provides an updated and interactive tool that could have value for species selection and management in various areas of the USA.

The hardiness map is used diligently by scientists and others in the horticultural community, yet is rarely mentioned in forage management literature (Baron and Belanger, 2007). Instead, ecoregions for adaptation of grasslands and forage species are usually focused on energy balance (Gates, 1980), growing degree days (Hall et al., 2009), precipitation balance including evaporation (Bailey, 1996), and soil and climate effects (Hannaway et al., 2005). These adaptation regions are less familiar with the forage and grassland community than the hardiness map is with horticulturalists. Seemingly the Plant Hardiness Zone Map could be made more practical for forage and pasture applications if upgraded to include some aspect of precipitation efficiency and/or perhaps soil issues like erosion potential. This approach and understanding will become more critical for adaptation as climate change occurs, which will lead to greater public concern about conservation and sustainability.

Further, more research information is needed on minor forage species or those species, including forbs, that may have potential as forage crops in an area. The USDA-ARS Plant Introduction Stations, especially the North Central Regional Plant Introduction Station in Ames, Iowa, and the Western Regional Plant Introduction Station in Pullman, Washington, play significant roles in evaluation of introduced legumes and cool-season grasses. Each site has primary responsibility for appropriate genera to acquire and evaluate new plant germplasm and to establish a maintenance program. These stations play significant roles in assessing areas of potential adaptation of introduced species for forage and assist with initial seed supplies of adapted species that may fit niche areas or have values that go beyond forage production.



**FIGURE 4.7.** The 2012 version of the USDA Plant Hardiness Map shows revision of the adaptation zones over previous maps due to a stronger database. Note temperature isolines are generally oriented east-west except near water bodies. Zone 10 is down to  $-1^{\circ}\text{C}$ , Zone 8 is down to  $-12^{\circ}\text{C}$ , Zone 6 is down to  $-23^{\circ}\text{C}$ , Zone 4 is down to  $-34^{\circ}\text{C}$ , and Zone 2 is down to  $-46^{\circ}\text{C}$ . Image courtesy of USDA.



**FIGURE 4.8.** Locations of the 27 USDA-NRCS Plant Material Centers that evaluate new plants for adaptation and basic management principles for conservation purposes. Centers also provide seed to commercial seed growers who increase the supply for use by landowners. Image courtesy of USDA-NRCS.

In addition, USDA-NRCS maintains a network of 27 regional Plant Materials Centers that help meet the growing interest in use of native plants and some introductions, especially those unique plants that may help solve conservation problems (Fig. 4.8). The centers locate and evaluate plants for conservation traits and make these materials available



Cost-effective solutions for conservation objectives require coordinated approaches that involve NRCS, other federal and state government agencies, agricultural experiment stations, cooperative extension service, private groups, and individuals.”

to commercial growers who provide plant materials to the public. Evaluations involve some research and result in application-oriented technology for the region including technical publications, fact sheets, identification, and release of conservation plants for further research and land restoration. The Centers have released over 600 grasses, legumes, forbs, shrubs, and trees for conservation purposes.

It is clear that plants offer versatility and a cost-effective tool for long-term protection and improvement of the environment. It would be helpful to the total effort if there was more applied research to determine best management practices for these new conservation plants. Cost-effective solutions for conservation objectives require coordinated approaches that involve NRCS, other federal and state government agencies, agricultural experiment stations, cooperative extension service, private groups, and individuals. As conservation issues and ecosystem services increase in importance, there will be even greater needs for education and evaluation of management options to maintain credibility and meet the growing demand.

Cooperative extension, NRCS field staff, and private organizations have direct connection to provide timely and appropriate information to landowners, managers, and the public about conservation issues. In addition, Plant Materials Centers provide vital plant data to support decision-making tools such as the Revised Universal Soil Loss Equation (RUSLE 2), Wind Erosion Prediction System (WEPS), and Grazingland Spatial Analysis Tool (GSAT). These tools are used in NRCS field offices to assist landowners conserve the nation's natural resources. It is critical that effective linkages among the key players are maintained so messages transferred are consistent and based on available research.

### Harvest Intervals and Stubble Height

Considerable literature documents how general principles of growth, regrowth, cutting frequency, residual leaf area, and reserves of carbohydrate and nitrogen affect regrowth of most major forage species (Fig. 4.1; MacAdam and Nelson, 2003). Implications from water stress (leaf growth is reduced more than root growth), inundation (roots are deprived of

oxygen), temperature stresses (too cold or too hot affects metabolic processes and growth), and fertilization regimes (nitrogen usually stimulates growth of grasses at the expense of reserve storage and reduces N fixation by legumes) on regrowth have been well developed for the major species. And these basic principles can be applied directly to their management. In addition, understanding local soils and climates helps determine the best management to be used. Local knowledge can be based on field demonstrations, especially those not novel enough to be published in refereed journals, or on broad experience of professionals.

Basic principles of forage management have been assembled into good extension publications that are based on published science and observations. For example, Rayburn (1993), in West Virginia, discusses growth and development of cool-season grasses and legumes to explain how these processes can be managed to optimize production and utilization. He emphasizes allowing reserves to be restored during spring growth before harvesting alfalfa, red clover, orchardgrass, and tall fescue for hay or silage. At this stage the yield advantage occurs by leaving a short stubble (5 to 8 cm), and regrowth is rapid. But quality of forage may be lower as cutting height is reduced since the lower canopy is mainly stem. Subsequent regrowths of alfalfa or red clover can be cut infrequently to leave a short stubble because they are able to restore reserves and depend very little on leaf area. This knowledge was further supported in research-based extension recommendations for stubble height of alfalfa in Wisconsin (Wiersma et al., 2007).

In contrast with alfalfa and red clover, cool-season grasses shift in growth habit after first cutting. Vegetative regrowths in West Virginia should have about 10 cm of stubble to ensure adequate leaf area to support regrowth (Rayburn, 1993). This recommendation is consistent with extension recommendations from Minnesota (Peterson and Thomas, 2008) in which they suggest grasses cut infrequently, especially during summer, should retain a stubble height of about 10 cm. In addition to providing sufficient leaf area to support regrowth, they emphasize the value of leaf area for shading to reduce soil temperatures,



reduce soil moisture evaporation, and provide competition with weed seedlings.

Peterson and Thomas (2008) gave further guidance on how cutting height could be used to maintain desired alfalfa-grass proportions in hay fields by leaving shorter stubble in summer to favor the legume or a longer stubble to favor grass. Further, they ranked grasses according to sensitivity to leave 3.5-cm of stubble compared with 10 cm citing research data from Wisconsin. Smooth brome grass and timothy were more sensitive to close cutting than were orchardgrass, reed canarygrass, and tall fescue. The effect of increasing stubble height on forage quality of both alfalfa and grasses has been found to be minimal (Parsons et al., 2009; Parsons et al. 2011). In Georgia tall fescue that was endophyte infected was not affected by cutting at 3-wk intervals at 3.8 cm or 7.6 cm. But yields of the same cultivars without endophyte were about 25% lower when cut at 3.8 cm (Hoveland et al., 1997). It is clear that extension specialists are aware of research in

surrounding areas and can effectively apply the principles to the local condition. For example, use of disc mowers and short cutting heights can shift bermudagrass–tall fescue mixtures rather quickly to a bermudagrass monoculture.

Leaving a tall stubble height is generally considered to be more important for upright-growing warm-season grasses than for cool-season grasses, especially with frequent defoliation (Anderson and Matches, 1983). Responses to stubble height and frequency of cutting have been well documented for most upright warm-season grass species, and information is available in extension publications. But there is a shortage of emphasis on how environments affect responses and delivery of ecosystem services. For example, proper cutting height and frequency are critical for maintenance of native warm-season grasses in dryer areas of the eastern Great Plains (Owensby et al., 1974; Mitchell et al., 1994) and for bermudagrass in warmer areas of the South (Ethredge et al., 1973). But

Grassed waterway is part of the conservation plan in Iowa. NRCS photo by Lynn Betts.

there is evidence from eastern states that these native warm-season grasses can tolerate closer and more frequent cutting in cooler areas with more rainfall (e.g., Forwood and Magai, 1992). Thus, similar to other studies with a range of forage plants (Balasko and Nelson, 2003; McGraw and Nelson, 2003; Redfearn and Nelson, 2003; Sollenberger and Collins, 2003), plants grown in lower stress environments, due to either biotic or abiotic challenges, are better able to tolerate close and frequent harvest.

### Moisture Management for Curing and Storing

A major goal of forage and silage management is to harvest when the crop is at the optimum stage for economic return, but this goal is further affected by need to preserve as much yield and quality as possible during drying, packaging, and storage periods. Rapid drying is the most important factor to achieve proper moisture content for storage with least loss in dry matter, especially leaves. Standing forage is typically 75–85% moisture and needs to be dried quickly to less than 70% moisture for silage, 50–60% for haylage, and about 20% for baling as hay (Rotz and Muck, 1994).

About 25–30% of the total water from stems and leaves is lost rapidly through stomata

for the first hr after cutting; after this time stomata close as plants wilt. Loss of remaining water through waxy layers on the stem and leaves is hastened if stems are crushed by a roll conditioner, which is better for legumes than crimping, which breaks the stem every few cm (Rotz, 1995), or scratched mechanically by a flail mower or a tine conditioner, which is better for grasses (Klinner, 1976; Digman et al., 2011). A thick forage mass going through the roller or flail mower decreases amount of conditioning received so operational speed is a factor. Final drying from 30–40% moisture to 15–20% for baling is slowest, during which time forage is most subject to damage from rain or high humidity. While reducing probability of weather damage, conditioning may lead to increased handling losses later.

In general, flail mower conditioners have greater power requirements than sickle-mower roll-type conditioners because of the need to accelerate and convey cut forage by blade force, which leads to greater field losses of small pieces (McRandal and McNulty, 1978; Rotz and Sprott, 1984). Minimum blade velocity for cutting grass or oat straw was 20 m s<sup>-1</sup>, and power required for cutting actually decreased when blade velocity was increased to 60 m s<sup>-1</sup> (McRandal and McNulty, 1978). In their field evaluations with eight grasses and oat straw, at a blade velocity of 78 m s<sup>-1</sup> and forward velocity of 5.5 km h<sup>-1</sup>, total power consumption increased linearly as crop density increased from 0.95 to 5.4 kg m<sup>-2</sup>. Throughout, energy to cut stems was minimal (3%) compared with that needed to accelerate and propel forage out of the machine (> 50%). Using a disc rotary cutter, actual stubble height increased from near the fixed height of 5.0 cm at forward velocity of 5.5 km h<sup>-1</sup> up to 6.3 cm of nonharvested stubble (1.8% field loss) at 14.2 km h<sup>-1</sup> (Ponican and Lichar, 2004). Losses of small pieces and other breakage due to swathing of forage cut with a disc rotary mower also increased from about 1.5% up to 6.4% as raking velocity increased.

Solar radiation is the most important factor affecting drying in the swath followed in order by air temperature, relative humidity, wind speed, and soil moisture (Rotz and Chen, 1985). Therefore, the upper surface of the swath dries most rapidly indicating the

Conservationist teaching landowners about grasses for buffer strips. NRCS photo by Bob Nichols.

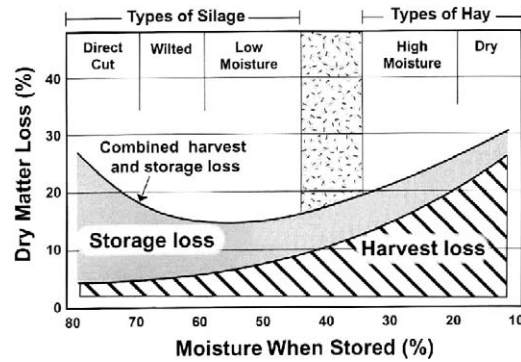


advantage of having wide windrows that are not thick. It also indicates why tedding or turning the windrow increases rate of drying. Forage may increase in moisture content due to absorption of water vapor from air during times of high humidity, mainly during the night, or from dew formation when liquid form is absorbed into dry inner parts of leaves and stems (Rotz, 1995). Thereafter, drying needs to resume, and it takes more time before forage reaches proper moisture content for storage.

Rainfall on the windrow is particularly challenging because it can move into tissues as liquid, like dew, and if duration and intensity are great enough some rain will pass through the forage swath to increase soil water content. Surface water on the plants can dry rather rapidly after rain ceases depending on solar radiation and relative humidity. Water absorbed by plant tissue dries slower, and high humidity due to evaporation within the swath will be a further deterrent. With light rain of short duration a wide swath will retain a higher amount of water on plant surfaces than a narrow swath and will dry quickly. With a heavy rain the swath width makes little difference (Rotz, 1995). Conditioned forage may absorb more water into plant tissue than nonconditioned forage during rain events (Rotz, 1995).

Swath manipulation by tedding, inversion, or raking can speed drying since the top of the swath dries faster than the bottom. But there is leaf loss that depends on moisture content (Fig. 4.9). Further, each field operation increases fuel, labor, and machinery costs and increases leaf loss. Leaf loss of grasses from tedding is only about 25% that of alfalfa (Savoie, 1987). Routine tedding or inverting is rarely cost effective for legumes due to high leaf loss (Rotz and Savoie, 1991) but may be cost effective with grass crops for hay (McGechan, 1990).

Based on summary data from Rotz and Muck (1994), harvest losses of legumes averaged 1% for mowing, 2% for mowing and conditioning, 3% for tedding, 1% for swath inversion, 5% for raking, and about 4% for baling. With grasses losses from cutting and conditioning and from tedding were slightly lower than for legumes, whereas losses from other operations were similar. But the literature is consistent



**FIGURE 4.9.** Typical losses in dry matter when legume-grass forage is stored at various moisture levels. Note losses in haymaking are due mainly to field situations, whereas those for silage making are due mainly to storage conditions. Adapted from Collins and Owens (1993).

that moisture content for both should be above 30% for raking.

Some dry matter loss during handling and storage is unavoidable; it usually affects leaf loss, so proportional loss in quality is greater than loss in yield and depends largely on moisture content of forage (Fig. 4.9). Losses are primarily during storage for silage that is preserved at 60% moisture, whereas losses are mostly field losses for hay that is baled at 15% moisture (Fig. 4.9). Comprehensive research reviews conclude the most important factors leading to loss are respiration, leaf shatter, microbial activity, and color bleaching (Rotz and Muck, 1994; Collins and Coblenz, 2007). Minimal loss with near perfect conditions is about 15% of total dry matter and should be a goal (Rotz and Abrams, 1988). Based on five research reports, Rotz and Muck (1994) concluded average losses in hay making are between 24% and 28%. This suggests there is room for improvement.

Several research studies support baling hay at 20% moisture or less for long-term storage. Most published studies showed losses during indoor storage are about 5% for both legumes and grasses, but are about 15% for legume bales stored outdoors and about 12% for grass bales when both are stored off the ground on rocks or a platform. These summations support the NRCS practice standard for forage handling and storage.



Some dry matter loss during handling and storage is unavoidable; it usually affects leaf loss, so proportional loss in quality is greater than loss in yield”



Conservationist and landowner discuss a management plan.  
Photo by Paul Fusco, NRCS.

Weather-induced losses are a major consideration in harvest management. Short intervals between rain events and the resulting high humidity require critical harvest timing to minimize losses due to weathering and to reduce soil compaction from heavy equipment on wet soils. During first harvest in spring the time required between cutting and forage removal from the field can be a few hours for preservation of silage, about 2 d for packaging and storing as haylage and 3 to 4 d when baled and stored as hay. Spring weather patterns in much of the eastern USA do not have sufficient dry periods to cut at the proper harvest stage and store quality hay. For these reasons, many producers accept loss of hay quality by delaying harvest, which allows plants to become more mature but coincides with less weather risk. However, harvest delay may provide some wildlife and environmental benefits.

### Estimating Moisture Content of the Forage

Measuring moisture content of windrows is the best way to assure forage is the correct moisture for storage as silage or hay. There are many electronic moisture meters available commercially for field use, but accuracy is questionable with errors often being 5 or more percentage units of moisture, which is too high for hay. Most meters are based on measures of capacitance or conductance and are not acceptable for assessing forage suitability for ensiling. Meters using electrical resistance are also not useful for silage (Prairie Agricultural Machinery Institute, 1993). There are several good laboratory methods for measuring moisture content, but they are time consuming and not suitable for field applications. An intermediate method that may have some merit would be to take a sample from the

entire depth of the windrow, weigh the fresh sample, place it in a microwave to dry, and then weigh the sample again. This method requires experience to remove all water without charring the sample.

Most methods used are nonscientific and based on farmer experience; for example, they may involve holding a sample of parallel stems and leaves that is about 5 cm in diameter in both hands, and then twisting the sample back and forth. If stems break after a few twists, the forage is dry enough to bale. For silage, a sample of cut forage can be squeezed into a ball that is allowed to expand on the open hand. If the ball gradually opens, the moisture content is acceptable for silage. If it is too wet, the ball will not expand very much. In both cases experience is helpful, but not quantitative, as stage of maturity and species of plants will cause samples to react differently. Unfortunately there are no defined methods for ease and accuracy for estimating moisture content in the field. This would be a good research contribution.

### Conserving Carbohydrates in the Forage

Carbohydrates in forage should be conserved as much as possible during drying and handling processes. Respiration of cut forage continues rapid use of carbohydrates for 5 to 10 hr after cutting, which extends beyond closure of stomata (Collins and Coblenz, 2007) and continues until moisture content is reduced to about 40% (Klinner, 1976). Respiration requires sugars and reduces rapidly digestible carbohydrate in forage, especially from leaves with their superior forage quality; sugars are needed for bacterial fermentation during silage making (Muck and Kung, 2007). Due to high buffering capacity of proteins and mineral compounds in forage, both of which are higher in concentration in legumes, it requires more carbohydrate to make quality silage from legumes than grasses.

Plant carbohydrates are higher in concentration at low temperatures than high temperatures due to reduced respiration, are higher in the afternoon than in the morning due to photosynthesis, are higher in leaves than stems, and are generally higher in cool-season grasses than legumes or warm-season grasses

(Moore and Hatfield, 1994; Collins and Coblenz, 2007). Some research, especially in the West, suggests forage should be cut in late afternoon when carbohydrate concentrations are elevated to improve forage quality (Burns et al., 2005). Diurnal variation in carbohydrate concentrations also occurs in the East (e.g., Morin et al., 2011) but appears to have less practical value since there is more cloud cover and lower photosynthesis, and initial drying occurs in late afternoon when humidity increases, especially during night. Lower carbohydrate concentrations and slower drying likely offset the potential advantage.

### Use of Drying Aids and Preservatives

Chemical treatments have been used to increase rate of drying, particularly application of a water solution of potassium carbonate at mowing (Rotz, 1995). The chemical reduces cuticle resistance to facilitate faster moisture loss from the plant. Other chemicals are reputed to open stomata or disrupt the cuticle but have not worked as effectively. The mechanics for applying potassium carbonate have been worked out for alfalfa, and when used properly on days with high solar radiation, drying time for baling hay can be reduced by 1 d. Economic assessment is not consistent. The chemical also works to improve drying rates for grasses but is much less effective than for alfalfa, which has higher forage value and is more subject to weather damage and bleaching in the field.

Moist hay can be preserved by use of a range of compounds, mainly those that inhibit microbial activity (Collins, 1995). Chemicals that are effective include organic acids such as propionic acid and ammonium propionate that control molding and heating of moist hay by preventing growth of fungi. In general, hay with higher moisture requires a higher acid concentration to inhibit microbial growth. In most cases with chemical treatment, storage losses are reduced and forage quality is retained. Animal acceptance of treated hay is generally not a problem. Using correct rates can be a challenge since moisture content of forage is variable across a field. In addition, application usually occurs as the windrow enters the baler, and distribution of the chemical should be uniform within the bale. Further, most organic acid treatments are now buffered, so they are less corrosive to equipment.



Chemical treatments have been used to increase rate of drying, particularly application of a water solution of potassium carbonate at mowing.”



There were insufficient data on minor forage species to be confident about having the scientific base for management.”

Ammonia compounds reduce microbial growth (Woolford and Tetlow, 1984) to be effective preservatives for moist hay under plastic (Moore et al., 1985). Urea added at 7 g kg<sup>-1</sup> to high-moisture tall fescue hay reduced mold and yeasts to about 15% of the control (Henning et al., 1990). Ammonia treatment also improved fiber digestibility and nitrogen content of low-quality grass hays like mature orchardgrass (Moore and Lechtenberg, 1987). Similar results occurred with urea-treated tall fescue hay. The treated orchardgrass hay also had higher forage intake and dry matter digestibility. Treatment of hay bales with anhydrous ammonia under plastic, especially bales with high moisture content, has been an effective way to preserve forage and also to increase protein content and digestibility of fiber fractions. Urea is an easy and effective way to treat hay since plant tissue naturally contains adequate activity of urease enzyme to convert urea to ammonia. These ammonia treatments improved digestibility of grass hays more than legume hays (Knapp et al., 1975).

In summary, good research data are available for most practices to harvest, cure, and store major forage species. Fortunately most harvest practices are based on plant development and are transferable to nearby states. A gradient in temperature exists that leads to species shifts in adaptation according to latitude from north to south that are based largely on winter and summer temperatures (e.g., Fig. 4.7). Likewise, a rainfall gradient occurs primarily from west to east according to latitude. In general adaptation is affected more by latitude than longitude. But water stress levels tend to be different from west to east and may alter the management needed to offset stresses for plant persistence and for various types of wildlife. The plant hardiness map (Fig. 4.7) could be enhanced by adding information on soil types and erosion potentials to better consider adaptation of forage species and offer guidelines to manage soil erosion and water quality.

There were insufficient data on minor forage species to be confident about having the scientific base for management. This will be critical because of growing interest in using native species and other minor-use species, especially in niche areas and for specific purposes. For example, several native legumes

are known to have potential in hay and silage systems, and may offer better potential for wildlife, yet there are few data.

## PURPOSE 2: PROMOTE VIGOROUS PLANT REGROWTH

### Stored Reserves and Leaf Area

Vigorous regrowth is desired for regaining maximum light interception by forage leaves to shade the soil and provide competition with weedy species. Vigorous regrowth of both legumes and grasses depends on the status of carbohydrate and nitrogen that are stored in plant parts that remain after cutting (Volenc et al., 1996; Volenc and Nelson, 2007). Carbohydrate, mainly starch, and nitrogen, usually as vegetative storage proteins, are stored in taproots of legumes and in stolons and rhizomes. Cool-season grasses store carbohydrate as fructan, a polymer of fructose, and vegetative storage proteins in stem bases and lower internodes. Warm-season perennial grasses store starch and nitrogen compounds in the lower stem. In general, the upright-growing grasses contain a larger supply of carbohydrate reserves when cut to leave tall stubble (Risser and Parton, 1982). Locations and roles of nitrogen storage in more prostrate growing warm-season grasses such as bermudagrass and bahiagrass are less understood.

Cutting forage plants removes leaf area and reduces photosynthesis, immediately placing plants in a negative carbon and nitrogen balance (Volenc and Nelson, 2007). Root growth of grasses slows within a few hours after cutting and may stop temporarily or even die depending on the amount of leaf area removed. Similarly, cutting causes nitrogen fixation by legumes to slow dramatically or even stop. The reserves are used to develop new leaf area and support respiration of the nonphotosynthetic parts. The negative balance continues for up to 14 d after cutting, until leaf area is sufficient to support the carbohydrate requirements, roots grow again, and nitrogen fixation again becomes active. Reserve levels will be low at cutting if the duration from the previous cutting is short or if temperatures are high. In these cases, taller stubble should be left that has live leaf area. Residual leaf area provides photosynthate so plants regain a positive balance sooner, some root growth

can continue, soil is shaded to reduce air and soil temperature, and plant respiration rate is slowed.

Regrowths originate from axillary meristems near soil level (Nelson, 1996; Moser and Nelson, 2003; Skinner and Moore, 2007). After cutting, buds of most legumes arise from the crown area or from lateral stems, stolons, or rhizomes. Leaves of cool-season grasses regrow from intercalary meristems located at bases of each leaf sheath. In addition, some grasses such as smooth brome grass, reed canarygrass, and switchgrass have rhizomes with axillary buds that lead to lateral spread. Since leaf area is reduced after cutting, especially with grasses with an upright growth habit that are harvested mechanically, these meristems depend largely on carbohydrate and nitrogen reserves (Volenc and Nelson, 2007). Grasses with high tiller density and substantial leaf area near ground level such as Kentucky bluegrass depend less on stored reserves and mainly on leaf area for carbohydrate supply during regrowth.

In summation, the principles discussed above are well known and have been researched for most major species, and appropriate management practices have emerged (Moser and Nelson, 2003; Skinner and Moore, 2007). Practice Standard 511 recognizes these principles and appropriately gives them emphasis. There is concern, however, that less-used forage species, mainly legumes and forbs, have potential for commercial use, but regrowth processes and adaptation are not clearly understood from research. This weakness can lead to lack of success in practical situations when managers know the potentials, but not the best options for management.

### PURPOSE 3: MANAGE TO MAINTAIN DESIRED SPECIES

Hay and silage are usually made from single-species fields of a perennial grass or alfalfa, or from mixtures of two or three species that often include a legume. Management to retain monocultures is generally associated with weed management to maintain a vigorous condition for a high-quality forage species such as alfalfa for dairy cattle. In most cases the legume component of a legume-grass mixture is used as the management guideline



since legume persistence and production are more sensitive than grasses to management treatments. Particularly in the case of variable soils within a field, increased species diversity can lead to increased productivity, due to niche partitioning and other factors (Hector and Loreau, 2005).

Cutting height is a critical management decision since it affects yield and quality of forage harvested, but it also affects persistence of many species and environmental services provided. Proper cutting height should be used to promote vigor and health of desired species. Fortunately this has been researched for major forage legumes (e.g., Buxton et al., 1985; Buxton and Hornstein, 1986) and grasses (Buxton and Marten, 1989; Buxton, 1990). For example, alfalfa uses stored reserves almost exclusively in early regrowth; if reserves are high it is not critical to leave leaf area at cutting (Monson, 1966; Sheaffer et al., 1988). In contrast, half or more of the energy for regrowth of cool-season grasses can be from photosynthesis of residual leaf area (Ward and Blaser, 1961; Booysen and Nelson, 1975). Thus, cutting height can be used to maintain or regain species balance in a mixture.

Several studies show leaving only 3 to 5 cm of stubble gives good regrowth of alfalfa when an

Interseeding native grasses into a cool-season grass field in Iowa. NRCS photo by Lynn Betts.



Soil temperatures can increase markedly if stubble does not provide shade.”

interval of 30 to 40 d occurs between cuttings. A taller cutting height for alfalfa was beneficial only when plants were cut frequently (Smith and Nelson, 1967), but leaving 8 to 10 cm of leafy stubble is recommended for birdsfoot trefoil. In contrast with alfalfa, birdsfoot trefoil stores only small amounts of reserves during the summer, and regrowth depends nearly exclusively on photosynthesis of residual leaf area. In general, reserves in red clover roots respond similar to the pattern observed for alfalfa (Smith, 1962), and those of crown vetch (Langville and McKee, 1968) respond much like birdsfoot trefoil. Kura clover had higher forage yield with 4-cm stubble height than with 10-cm stubble height (Kim and Albrecht, 2011). Annual legumes such as korean and kobe lepedeas store very little reserve in the roots and depend on leaf area remaining after cutting to support regrowth (Davis et al., 1994, 1995).

Soil temperatures can increase markedly if stubble does not provide shade. In Massachusetts, when spring growth of orchardgrass was cut and removed, leaving 5 cm of stubble, soil temperature the next day increased by 14°C (Colby et al., 1966). High temperatures increase respiration and heat stress on young tillers of cool-season grasses. In contrast, Kentucky bluegrass is a sod former that retains leaf area near the soil surface and can be cut shorter. There is evidence that leaving a tall stubble in late fall cuttings of upright-growing grasses and legumes helps catch snow and reduces soil freezing and thawing that leads to frost heaving and winter kill. Most of these relationships have been researched for major species, and practical results are published in extension outlets for a state or region.

Stem tissue is lower in quality than leaf tissue, so whereas forage yield of alfalfa and upright grasses is greater when cut shorter, the added amount of stem tissue generally reduces quality of hay or silage (Buxton, 1990). Further, the lowest sections of stems are lower in quality than upper sections, and they support the oldest, lowest quality leaves of forage legumes (e.g., Buxton et al., 1985; Buxton and Hornstein, 1986) and grasses (Buxton and Marten, 1989; Buxton, 1990). In West Virginia, monocultures of bermudagrass and

caucasian bluestem with somewhat prostrate growth had higher forage yield than did upright growing switchgrass when cutting began early in the season (Belesky and Fedders, 1995). However, growth rates for all were higher when 75% of the canopy was removed compared with 50% removal. They concluded that bermudagrass and caucasian bluestem were better adapted to frequent defoliation, whereas switchgrass would be better for conserved forage. Thus, cutting to shorter stubble heights usually increases forage yield, but may reduce forage quality (Burger et al., 1962). This economic relationship needs to be understood while managing legume-grass mixtures.

In addition, since forage grasses store reserves in lower stem internodes and stem bases, more reserves are removed by close cutting which reduces regrowth vigor of cool-season (Matches, 1969) and warm-season grasses (Rains et al., 1975). Close cutting also opens the canopy, which allows shifts in legume-grass proportions (Fales et al., 1996) and greater invasion of weeds in monocultures of alfalfa (Peters and Linscott, 1988). It also shifts the proportions of cool- and warm-season grasses growing in mixture.

### Managing for the Desired Species Mix

Matching maturity times of legume and grass components is critical since management is easier when both types of plants are at the appropriate growth stage when harvested, especially spring growth. Morphological and physiological relationships are important, but recent research on mixtures has been minimal. Exceptions relate to the endophyte status of tall fescue, which has very little effect on compatibility with some legume species (e.g., alfalfa; Hoveland et al. 1997), and the quest for legumes that are compatible with native warm-season perennial grasses in the Midwest and with a range of grass species in the South.

Review of several extension publications show a sound scientific basis for management of mixtures of most major species (e.g., Koenig et al., 2002, in Utah; Rayburn, 2002, in West Virginia; Johnson, 2007, in Indiana; Barnhart and Sternweis, 2009, in Iowa; Hancock et al., 2011, in Georgia). Over a period of years, legume-grass mixtures are often higher yielding than monocultures of any of the components,

more persistent, better adapted to variable soils in the field, more resistant to weed encroachment, have better erosion control, and compared with a monoculture of legume are easier to harvest and cure.

Most research has been on alfalfa-grass mixtures with coalescence around use of orchardgrass that matches alfalfa in stages of maturity, improves seasonal distribution of production, gives good regrowth and competition with weeds in summer, and improves ground cover during winter (Wolf and Smith, 1963). Compared with grass monocultures in Iowa, binary mixtures of alfalfa, birdsfoot trefoil, and kura clover all improved seasonal growth distribution with smooth brome grass, orchardgrass, and intermediate wheatgrass (Sleugh et al., 2000). In contrast, tall fescue and timothy tend to match best with red clover, whereas studies with Kentucky bluegrass tend to focus on white clover, which is also low growing. Using appropriate cutting management, yield of an alfalfa-reed canary grass mixture in Minnesota was greater than reed canarygrass in mixture with birdsfoot trefoil or red clover, while yields with ladino clover were lowest (Heichel and Henjum, 1991). Nitrogen fixation by legumes was closely related to their yield in the mixture. In mixture with reed canarygrass, alfalfa fixed 175 kg N ha<sup>-1</sup>, whereas birdsfoot trefoil fixed 77 kg N ha<sup>-1</sup>, red clover fixed 63 kg N ha<sup>-1</sup>, and ladino clover fixed only 9 kg N ha<sup>-1</sup>.

Several extension publications suggest a threshold of about 25–30% legume in mixtures to gain the benefits of legumes in a mixture. Grass monocultures fertilized with high N rates have higher yield potential than legume-grass mixtures without N (Wolf and Smith, 1963; Sleugh et al., 2000), whereas legume-grass mixtures have higher forage quality, better weed control, and improved stand persistence. But mixtures are more difficult to maintain because of species differences in growth habits and in carbohydrate reserves at cutting (Kust and Smith, 1961). Shorter stubble usually favors alfalfa, whereas taller stubble heights tend to favor the grass component. Fortunately, good educational information is available on the basic principles of management of mixtures of legumes and cool-season grasses that include effects of light interception and N nutrition. These are also regulated by liming that favors the legume, K nutrition that favors legumes that are less competitive for K at low rates, cutting height, cutting frequency, timing of fertilization, and reseeding practices.

Nutrient management is an important tool for maintaining desired proportions of legume and grass species in the field. Nearly all experiment stations recommend no N fertilizer be used on mixes including at least 25% legumes since N tends to stimulate grasses making them too competitive. Conversely, fertilization with K improves tolerance of environmental stresses; grasses benefit most at low rates, while legumes

“

mixtures are more difficult to maintain because of species differences in growth habits and in carbohydrate reserves at cutting.”



Native grasses are part of a buffer system to aid wildlife and the environment. NRCS photo by Lynn Betts.



Discussion about pasture management in Louisiana. NRCS photo by Bob Nichols.

benefit most at high rates. Most experiment stations suggest fertilization of legume-grass hayfields with K after first harvest to improve tolerance to drought and heat or in early autumn to improve winter survival (Meyer and Helm, 1994). These recommendations are based on good science and are effective. Dealing with manures as nutrient sources is more challenging and is discussed later in this chapter.

In summary, there is good research on the importance of legume-grass mixtures and management strategies to maintain both types of plants in the stand. Legumes are the most sensitive component, and, if they cannot be managed to persist or naturally reseed, they are usually overseeded periodically to increase stand density. Due to autotoxicity, alfalfa cannot be overseeded to increase stand density (Jennings and Nelson, 2002). Unfortunately there are few herbicides that can be used to control weeds in legume-grass mixtures.

#### **PURPOSE 4: MANAGE FORAGES FOR EFFECTIVE SOIL NUTRIENT UPTAKE**

Fields devoted to harvested forage lack the inherent nutrient recycling found in pasture systems (Brown, 1996). Replacement of nutrients removed is required for a sustainable system, and soil testing is essential for

documenting nutrient changes in soil over time (Wood et al., Chapter 5, this volume). Fertility management, including rates and timing, for mixed perennial forages can have dramatic effects on the species balance. Removal of nutrients by harvested forages can be estimated using published forage composition tables; however, forage composition of a particular field may deviate greatly from average values. Since both yield estimates and forage analysis are essential for using precision feed management, these data can also be used to help assess fertilizer needs for the crop.

While nutrient removal by forage is critical for economic returns to the producer, fate of applied nutrients that are not taken up is of environmental concern and needs to be minimized. This is covered to a great extent by Wood et al. (Chapter 5, this volume) and is supplemented here considering removal of forage to be stored for use as an animal feed.

#### **Nutrient Management for Yield and Persistence**

**Lime.** Soil nutrient levels must be assessed prior to establishment of perennial forages (Barker et al., Chapter 2, this volume). Natural soil pH is usually acidic in the eastern USA that was dominated by forest, but tends to be closer to neutral (pH = 7.0) in the dryer areas to the west that were dominated by prairie. Availability of nutrients in the soil is affected by pH, and it should be corrected to optimum for the species to be planted. If soil pH is too low for the sown species, lime should be applied and worked into soil prior to seeding. Appropriate soil pH (in water suspension) in northern states is approximately 6.5 to 7.0 for alfalfa, slightly lower for red clover and birdsfoot trefoil, and 5.8 to 6.5 for grasses (Brown, 1996). Recommended amounts of liming material are quantified using estimates of neutralizable activity in the surface soil. Actual recommendations based on local research may vary from state to state due to use of different calibration techniques.

**Nitrogen.** Nitrogen has the greatest effect on forage yield of all nutrients, and the most influence on forage quality and balance of a legume-grass mixture. Legumes fix most of the N that they require without need for added external N. Most studies on alfalfa have

concluded there is a reduction in N fixation with addition of readily available sources of N, but responses have been variable. For example, Shuler and Hannaway (1993) concluded biological N fixation can be completely inhibited by available soil nitrate, while other studies suggest that significant N fixation occurs in alfalfa, even when fertilizer N is applied at high rates (Cherney and Duxbury, 1994; Lamb et al., 1995). Reasons are unknown.

Rarely is N fertilizer (beyond N fixation) recommended for mixtures if the stand is at least 40% legume (Ketterings et al., 2007). Such estimates are based on experience, as there is no good soil test for N on which to base these recommendations. Once the legume component is reduced to less than 20% in a mixed legume-grass stand, the field is usually managed as a grass using N applications to increase yield, putting the legume at a competitive disadvantage and the grass component dominates.

Grass monocultures can respond to high levels of N fertilization (over 335 kg ha<sup>-1</sup> annually) under adequate moisture conditions (Hall et al., 2003). Rates above 250 kg ha<sup>-1</sup> annually, even with split applications, increase risks of nitrate leaching, and high forage nitrate concentrations that can affect animal health. Some grass species have lower yields and lower forage-N content, making them less efficient at removing soil nitrate. There are few species-specific N recommendations for cool-season grasses harvested for stored forage. Some states base N recommendations for grasses on average soil moisture availability (Anderson and Shapiro, 1990). Some Midwestern states base recommendations on projected yields of a specific species, ranging from 5.5 to 18 kg N Mg<sup>-1</sup> of forage in the Midwest (Brown, 1996). The economic optimum N rate is considerably higher in the Northeast, exceeding 27 kg N Mg<sup>-1</sup> of forage (Hall et al., 2003).

Potential environmental effects of N fertilization of grasses can be estimated by the amount of applied N that is not recovered in the harvested forage. The calculation is based on N recovered in fertilizer treatments minus N recovered by unfertilized controls. But the fate of the nonrecovered N is not known. Apparent-N recovery by perennial grasses at

fertilization rates of 225 to 270 kg N ha<sup>-1</sup> was variable and generally ranged between 50% and 70% (Vetsch and Russelle, 1999; Hall et al., 2003; Cherney and Cherney, 2006). Timothy typically has a significantly lower apparent-N recovery than other cool-season species (George et al., 1973; Hall et al., 2003). Increasing number of harvests per season will increase recovery (Hall et al., 2003), but splitting applications of N has not increased total N recovered or apparent N recovery (Vetsch and Russelle, 1999; Cherney and Cherney, 2006). Applying N just before rapid growth need is usually considered a good way to maximize recovery, but there are few studies that have evaluated this topic.

**Phosphorus.** Phosphorus recommendations are based on soil test results, although several different P extractants are used to test for soil-P depending on the state. Phosphorus recommendations also are based partly on whether soils were leached of P during formation (Brown, 1996), resulting in a wide range of recommended amounts. From a soil perspective, timing of P fertilization during the season does not appear important, but forage species differ in response. Phosphorus is important for N fixation in legumes, impacting both yield and persistence (Berg et al., 2007), and legumes are less efficient at extracting P from soils compared with grasses (Barker and Collins, 2003). Significant yield responses of grasses have been noted (Ludwick and Rumberg, 1976; Christians et al., 1979). Phosphorus has a greater effect on yield than on persistence in grasses.

Programs for gradually increasing soil-P should be reevaluated in this era of increased environmental concerns. Phosphorus content of forages does not fluctuate greatly, averaging approximately 0.33% of dry weight in grass silage and 0.34% in legume silage (DairyOne Forage Laboratory, Ithaca, NY). Phosphorus typically has been overfed to dairy cattle (Harris et al., 1990). The excess P usually ends up in the manure creating a disposal problem. This serious P-management problem should not be solved by limiting P availability and yield of plants but can be dealt with effectively by limiting P content of supplementary feeds in the diet (Van Horn et al., 1991; Esser et al., 2009; Bjelland et al., 2011).



excess P usually ends up in the manure creating a disposal problem.”



Priority fields for manure application should be those fields with nonlegume crops that could most benefit from manure nutrients.”

**Potassium.** Potassium has the same issues with extractants as those mentioned for P above. Unlike P, which has low water solubility, K is soluble so timing of applications on forage crops is important. Soil K is released naturally over winter so is relatively high in spring, indicating application of K to forage crops should be delayed until after first hay harvest. Potassium is essential for maintaining yields, reducing disease susceptibility, and increasing winter hardiness and stand survival. For alfalfa, an application of K later in the season will help ensure that K is available to enhance plant survival over winter. For grasses, potassium fertilizer regimes should be controlled by K-supplying power of the soil and by total K removed per season (Cherney et al., 1998). Yield and persistence of alfalfa are strongly influenced by available soil K, while grasses are less dramatically affected (Cherney and Cherney, 2005). Yet K fertilization of grasses is critical for winter hardiness, especially for bermudagrass that receives high rates of N fertilizer.

Potassium concentration in forage crops is relatively high, is related to available soil K and can be higher in the crop than needed for high yield, resulting in significant removal by the crop. Potassium content of forages is considerably more variable than P, averaging 2.4% in grass silage and 2.8% in legumes (DairyOne Forage Laboratory, Ithaca, NY). In addition to amount of available K in the soil, concentration of K in grasses is influenced by grass species, forage age, and time of season, and also interacts strongly with N fertilization. Variability occurs in grasses because they exhibit luxury consumption at high rates of K, yet they also can tolerate lower levels of soil-test K than legumes (Joern and Volenec, 1996; Cherney et al., 2003).

### **Use of Animal Manures for Yield, Persistence, and Nutrient Management**

Animal manures supply both nutrients and organic matter to soil which are assets. Yet they can affect harvested forage negatively through excessive nutrient concentrations or through contamination of the soil surface. Type of animal generating the manure, amount of excreta versus bedding or litter, and manure storage system all affect application and use of manure (Simpson, 1991). Manure use for

establishment of perennial grasses, legumes, or legume-grass mixtures may increase yields if soil is deficient in P, K, S, or B (Ketterings et al., 2008). Inclusion of an annual companion crop is suggested to minimize N losses while perennial crops are slowly becoming established.

Established alfalfa and alfalfa-grass hayfields can be topdressed with cattle manure without loss of yield or quality; however, there may be risk of heavy metal accumulation in soils treated with poultry or swine manure (Nicholson et al., 1999; Wood et al., Chapter 5, this volume). Additional risks involved in manure applications to alfalfa include salt damage to new growth, pathogen contamination, and soil compaction and damage to plant crowns during application. The ratio of N to P in manures differs from the needs of forage plants. Therefore, manure application to meet N requirements of forage crops results in excess P application, with the additional disadvantage of N volatilization losses. Partial incorporation of manure using an aerator/tillage tool can reduce volatilization losses (Fuchs, 2002). Even though alfalfa has a deep rooting zone to capture nitrates low in the soil profile, high application rates of liquid manure (23,000 L ha<sup>-1</sup>) resulted in significant leaching (Daliparthi et al., 1994).

From a nutrient-use-efficiency standpoint, corn and forage grass fields tend to be preferred sites for manure application. Forage grasses have a high N requirement while minimizing nitrate leaching due to a fibrous root system. After two to four seasons of manure application, forage yields of perennial grasses were equal or higher than those fertilized with commercial N (Cherney et al., 2002; Cherney et al., 2010). Different times of manure application during the season did not affect yield or forage quality of cool-season grasses (Cherney et al., 2010). Alfalfa typically meets its nitrogen requirement through biological N fixation, so N from other sources such as manure is unnecessary if conditions for N fixation are satisfactory. Priority fields for manure application should be those fields with nonlegume crops that could most benefit from manure nutrients.

Current nutrient management plans for many states require that manure application to corn and forage grasses be limited to crop-N needs,

increasing the likelihood that some manure will need to be applied to forage legumes such as alfalfa or legume-grass fields. At some times these fields may be the only ones available and accessible for manure application. If legume monocultures continue to fix N in the presence of readily available N sources, uptake of manure N will be reduced, and the manure application could increase risk of N leaching. The risk is reduced if manure is applied to alfalfa-grass mixtures, in which case the grasses will use the manure N. The practice of applying manure shortly before plowing alfalfa or alfalfa-grass stands designated for rotation to corn or other crops should be strongly discouraged. Breakdown of alfalfa or alfalfa-grass by soil microorganisms alone supplies sufficient N for a corn crop under most conditions (Lawrence et al., 2008a).

The vast majority of broiler chickens in the USA are produced in southern states, resulting in a large broiler litter manure source for potential application on forage fields (Wood et al., Chapter 5, this volume). Mechanically harvested forage will reduce buildup of nutrients from poultry litter applications, and limited N fertilization will encourage mineral uptake of P, K, Cu, and Zn that would otherwise build up in soils (Evers, 2002; Pederson et al., 2002). Depending on rate and frequency of applications, poultry litter may increase levels of soil nutrients enough to adversely affect health of animals consuming harvested forage. Off-farm alternative uses for manures such as compost, mulch, or substrate for mushroom growing should be considered if forage fields are the only alternative and they already have excessively high nutrient levels.

### Manure or Soil Contamination of Forage

Manure carries a variety of pathogens that can live in soil for up to 1 yr (Stabel, 1998). *Salmonella*, *Listeria*, *Campylobacter*, and *E. coli* bacteria can be found in manure, along with the pathogenic protozoa *Cryptosporidium* and *Giardia*. There is risk of direct leakage from manure in buildings, in storage, or following spreading on land (Mawdsley et al., 1995). Manure pathogens may move laterally via surface or subsurface runoff and downward through sandy soils, cracking clay soils, or tile-drained soils (Geohring et al., 2001).

Some soil-borne pathogens will proliferate in improperly stored forage and be exposed to animals. Unpasteurized or raw milk can potentially carry a variety of serious pathogens including *Salmonella*, *Listeria*, and *E. coli*, and cheese made from raw milk can contain these same pathogens (CDC, 2007; Omicciolo et al., 2009). Ensiled forage that does not achieve a low pH can result in proliferation of *Clostridium botulinum*, a secondary fermentation, particularly if the stored forage is greater than 70% moisture. Botulism in stored hay is rare but possible if wet, anaerobic conditions exist.

Aerobic molding of hay or silage from *Aspergillus* and other aerobic fungi reduces palatability, but generally causes significant animal disorders only in horses. An exception occurs when mycotoxins are produced. *Aspergillus*, *Fusarium*, *Penicillium*, and *Alternaria* are all capable of producing mycotoxins in silage and haylage (Kuldau and Mansfield, 2006). Toxins from *Aspergillus* species are the most common in warmer climates, and aflatoxins and cyclopiazonic acid produced by *Aspergillus* species are passed in milk. *Fusarium* species generate toxins most efficiently at relatively cool temperatures, and these toxins are not reduced by ensiling (Gotlieb, 1997). Soil contamination and/or aerobic deterioration of silage also can result in proliferation of *Listeria* (Collins and Hannaway, 2003), a serious condition more commonly found in bale silage.

The most common pathogen in manure affecting animal health is *Mycobacterium paratuberculosis*, the causative agent of Johne's disease, which is an incurable, progressive disease in cattle. Research is underway to determine if it can spread to humans as Crohn's disease. Approximately 22% of US dairy herds contain animals infected with Johne's disease, although very few animals show clinical signs of the disease (Collins and Manning, 2005). Infected, subclinical animals can infect other animals for up to 10 yr before showing clinical symptoms, often following significant stress such as calving (Jansen and Godkin, 2005). Calves can become infected by ingesting a small amount of infected manure or milk. Regular monitoring of the herd for Johne's disease is strongly suggested.



Manure carries a variety of pathogens that can live in soil for up to 1 yr.”



Forage plant growth habit and rooting architecture significantly affect the balance between runoff and infiltration.”

There are several methods to control spread of *M. paratuberculosis*. The bacterium is sensitive to pH; a surface lime application on fields receiving manure applications will reduce its survival. Young animals should not come in contact with pastures or stored forage that is potentially contaminated with manure. The bacteria survive on dry hay, but proper ensiling appears to greatly reduce populations (Katayama et al., 2001). If animals with Johne’s disease are known to be present in the herd, the manure should be applied on nonforage fields to minimize forage contamination. Spread of Johne’s disease is minimized if manure applications are delayed until after final forage harvest of the season. Manure contamination of harvested forage during the season is minimized if manure is applied during spring greenup or immediately after harvesting, before forage regrowth has accumulated. Manure or soil contaminating the surface of forage tissue increases risk of Johne’s disease or clostridial silage fermentation.

In summary, harvesting forage at the proper stage of maturity and moisture level for the storage system is a key practice to minimize pathogens and toxins in forage. Rapid harvest, tight packing, and oxygen exclusion for silage making are also essential (Collins and Owens, 2003). Feedout of forage, especially from bunker silos, must be at a rate per day that is rapid enough to avoid surface spoilage.

### Management Effects to Reduce Nutrient Runoff

Surface runoff and erosion may contaminate surface waters with P as well as manure pathogens (Sharpley et al., 1994). In general, forage crops reduce soil erosion by protecting the soil surface from raindrops (Karlen et al., 2007). The energy from raindrops is dissipated, preventing them from dispersing soil aggregates, thus increasing filtration and minimizing runoff. Forage plant growth habit and rooting architecture significantly affect the balance between runoff and infiltration. Sod-forming vegetation, particularly species with rhizomes such as reed canarygrass, reduces velocity of runoff and protects soil surfaces from erosion (Karlen et al., 2007).

Forages may serve a dual purpose as a forage crop and as a conservation buffer. Buffer

strips of perennial forages can play a major role in minimizing nutrient flow into surface waterways (Clausen et al., 2000; Liu et al., 2008). Contour buffer strips, field borders, filter strips, and grassed waterways may all be used for forage production (Karlen et al., 2007). Care should be taken when harvesting conservation buffers such as filter strips and waterways that are more likely to have wet soils. Heavy forage harvesting equipment can compact or produce ruts in the forage field, depending on soil moisture and soil type. Soil compaction decreases infiltration and can increase runoff. Ruts can also increase runoff by providing channels for water flow, depending on field slope and channel orientation.

If possible, manure applications should be timed to minimize the potential for a rain event soon after the application. Applications in summer and early fall are more likely to meet this criterion, when soils tend to be relatively dry. Precipitation directly following manure application will maximize chances for nutrient and pathogen runoff, as well as chances for leaching, macropore flow, and effluent losses through tile drains (Geohring et al., 2001). Partially incorporating manure into soil is a good manure management practice that reduces potential runoff losses from perennial forage fields (Fuchs, 2002; Lawrence et al., 2008b). Manure application, as well as harvest for hay or silage, should be restricted to fields with a slope that is less than 15%. Forage land with steeper slopes may be used for pasture, where runoff concerns exceed leaching issues. Leaching potential is greater in pastures compared to mechanically harvested forage fields (Karlen et al., 2007).

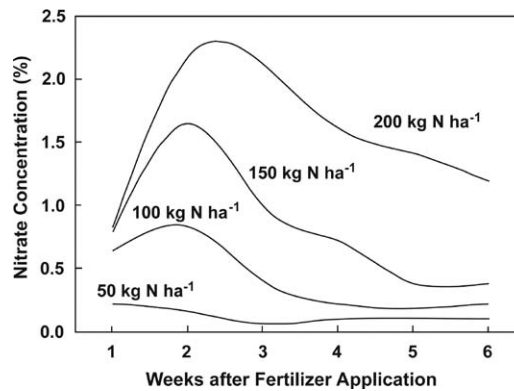
### Nutrient Imbalances and Effects on Livestock

Proper timing and rates of fertilization for forage crops will maximize yield and persistence and will result in high nutrient uptake. Just as overfertilization of field crops was common in the past, overfeeding of cattle also was viewed as cheap insurance for maximizing productivity. Forage crops can be managed and harvested to produce optimum quality forage for a given class of livestock. Ration balancing for each class of livestock can eliminate nutrient deficiencies, but nutrient excesses in forages are

most effectively controlled by soil fertility and harvest management.

Some forage crops contain toxic compounds in sufficiently high concentrations to harm animals. Examples are hydrocyanic acid in sorghums, ergot alkaloids in tall fescue, indole alkaloids in reed canarygrass, and phytoestrogens and coumarin in legumes. Harvesting plants at more advanced stages of growth for hay or silage greatly reduces the cyanide potential in sorghums (Collins and Hannaway, 2003). Alkaloids in tall fescue can be reduced to safe levels by use of endophyte-free seed (Sleper and West, 1996), although endophyte infection increases plant tolerance to water stress, insects, and disease. Nontoxic endophytes have been developed that increase plant persistence in tall fescue with minimal or no effect on livestock performance (Bouton et al., 2002). Growing infected tall fescue in mixture with a legume such as white or red clover or other grasses dilutes the toxicity level. Livestock disorders due to alkaloids in reed canarygrass can be minimized by use of low-alkaloid cultivars (Marten, 1989). Negative effects of most toxins can be minimized by dilution of the toxin source in the animal diet with other forage sources. Proper ensiling minimizes effects of most toxins except for cyanide potential and phytoestrogens (Collins and Hannaway, 2003).

Nutrient imbalances, such as grass tetany (hypomagnesaemia), and bloat are typically seasonal and most often associated with ingestion of fresh forage on pasture. Nitrate toxicity in grasses can be generated by high N fertilization, coupled with drought, frost, or prolonged cloudy conditions that slow growth. Under normal conditions nitrates accumulate rapidly in forage after fertilizer application, but with moderate rates are metabolized to other compounds within 3 wk (Fig. 4.10). Forage growth during drought is reduced, and nitrates can accumulate to high levels since they are not used to increase yield. These nitrates are stable and remain high if plants are harvested and stored as hay, but concentrations are reduced by about 50% when forage is ensiled. Alternative solutions include allowing plants to mature further or to cut higher to leave lower stem material.



**FIGURE 4.10.** Nitrogen fertilization effects on forage nitrate patterns in tall fescue depend on application rate and ability of growth processes to utilize accumulated nitrate compounds. From Collins and Hannaway (2003).

The primary nutrient imbalance associated with stored forage is high K content leading to potentially severe post-partum maladies in dairy cattle. As discussed above, K is subject to luxury consumption in grasses, which is aggravated by high N fertilization (Cherney et al., 1998). Controlling K inputs to a field of cool-season grasses utilized as dry cow forage, along with delayed harvest, can minimize K content of forage and potentially avoid milk fever and associated post-partum problems (Cherney et al., 2003; Cherney and Cherney, 2005). Warm-season grasses are usually lower in K concentration and have less risk.

## PURPOSE 5: MANAGE FORAGES TO CONTROL INSECTS, DISEASES, AND WEEDS

Control of insects, diseases, and weeds is most economic and usually based on maintaining a vigorous stand to provide a strong degree of biological control through healthy plants. Most forage cultivars are seeded and are highly heterogeneous in nature; therefore they have genotypic plasticity that allows adaptation to environmental or management conditions. Recognizing this, plant breeders have been primary contributors to disease control through selection and use of disease-resistant cultivars (Nelson and Burns, 2005; Lamb et al., 2006), although yield or quality may be only marginally changed. Most genetic progress has been made in disease resistance that may also favor persistence (Lamb et al., 2006). In only



Some forage crops contain toxic compounds in sufficiently high concentrations to harm animals.”



Conservation specialists evaluate a prescribed grazing practice in Arkansas. NRCS photo by Jeff Vanuga.

a few cases is it economic to use fungicides, bactericides, or nematicides in hay or silage plantings. Instead, the crop is usually harvested to remove the infected material with the expectation the regrowth will be less infected and the plants will survive. Conversely there is good evidence that leaf diseases can cause leaf death and loss, which reduces the digestibility and intake of the forage.

Principles of integrated pest management are most frequently used to control biotic stresses. These principles depend on knowledge of life cycles and management guidelines for the forage and life cycle of the specific disease, insect pest, or weed (Sulc and Lamp, 2007). Management can be altered by cutting at times in life cycles when plants are vigorous and the pathogen, pest, or weed is in a vulnerable stage. But this interaction also changes with time as new cultivars are introduced and management practices are changed. In some cases release of exotic insects or pathogens helped reduce pest or weed populations to near or below threshold levels. For example, several exotic parasites and some pathogens from Europe have been released to control alfalfa weevil. In some cases a forest or other crop must be nearby to provide habitat for survival of the parasite or pathogen. Desired long-term ecosystem solutions are based on a mix of biological control and

resistant cultivars. Most genetic progress has been made with alfalfa, due to private industry leadership and a very specialized seed industry that provides protection of proprietary cultivars (Lamb et al., 2006).

Potato leafhopper, another major insect pest of alfalfa, releases toxins as nymphs feed on leaves. Plants are stunted, and protein content of forage is reduced. This problem was less serious when harvests were made at late maturities (Graber and Sprague, 1935). Adults overwinter in the Deep South and move northward on wind currents to lay eggs in alfalfa fields. Harvest at near full bloom removed the forage before eggs hatched and nymphs developed. When better cultivars were introduced to allow earlier and more frequent harvest, eggs were laid in regrowth after first harvest and nymphs damaged plants before second harvest. Some damage also occurred in the third harvest. Use of insecticides was the first response, but this has been largely replaced by use of glandular-haired cultivars that deter egg laying (Sulc et al., 2002). Genetic resistance was increased such that today there is no economic damage on new glandular-haired cultivars.

In eastern states the egg hatch of alfalfa weevil in early spring allowed larval damage before the first harvest. It was too early to cut alfalfa, so insecticides were needed. Early regrowth after first harvest can be damaged, but little if any damage occurs in later harvests because adults leave the field. The weevils reduce yield some, with most effect being loss of forage quality since larva feed on young leaf blades. Several attempts were made to develop genetic resistance with very little success (Lamb et al., 2006), so other alternatives were researched. Gradually other insects were introduced and became established that parasitized the larval stages of the weevil (Sulc and Lamp, 2007). Biocontrol methods for weevil control usually are effective enough in much of the northern USA that insecticides are not needed on a regular basis (Radcliffe and Flanders, 1998).

Survival of fall-laid eggs of alfalfa weevil in basal parts of the stem leads to the early spring infestation the following year, especially in the geographic transition zone with milder winters. This major feeding comes early, ahead of the biocontrol agents, and requires some

intervention. Burning the stubble in winter or a late fall harvest increases winter kill of the eggs and delays major damage until spring-laid eggs hatch. But these management treatments open the canopy in fall and winter, which allows greater infestations of winter annual weeds and/or potential for plant heaving. Winter annual weeds such as henbit and chickweed tend to be prostrate and cover buds on crowns of alfalfa to reduce shoot number, yield, and competitiveness during spring. Farm managers in this zone must decide whether to harvest in late autumn and monitor winter annual weeds or not harvest in late autumn and monitor early hatch of weevils (Caddel et al., 1995).

Other insect problems occur infrequently or mainly in certain areas. Alfalfa snout beetle occurs near the St. Lawrence Seaway in northern New York and southern Canada, presumably introduced from Europe by ship traffic. Snout beetle larvae destroy alfalfa tap roots, and there is no practical control through management or pesticides. Fortunately the insect is flightless. Clover root curculio affects younger clover and alfalfa plants by girdling outer layers of root tissue to get food. Feeding reduces storage of carbohydrates and regrowth vigor and opens root tissue to pathogens that cause diseases and plant death. Fall armyworm infestations occur intermittently in forage crops in northern areas, and more routinely in southern areas where they can be very damaging to yield and plant vigor if not controlled, usually requiring an insecticide. State Agricultural Experiment Stations and Extension Services provide information on identification of insect pests and the array of ways they can be controlled. Invariably information focuses first on plant management to reduce the problem, with use of an insecticide as a last resort. Information generally cautions users about application of chemicals and restrictions on subsequent use of the forage.

Weeds are plants that compete strongly with desired forage plants to reduce yield, quality, or stand persistence, through competition for light, space, water, and nutrients. Weeds are more likely to be a problem during establishment, and again later in the life of the stand when the forage crop begins to decline. In these terms weeds in hayfields are

being redefined since nonplanted species like many forbs have good quality and contribute to yield. However, rarely will these species have the same degree of value as the planted forage, yet are major parts of the soil seed bank. Weed management of haylands starts during establishment, after which plant competition is the major method used to reduce encroachment, seed production, and survival of weeds. Vigorous regrowth of the forage is critical since many weeds that have germinated before cutting become established in thin stands during the forage regrowth period. Weeds in monocultures can be controlled by an array of chemical herbicides (Barker et al., Chapter 2, this volume).

Weeds are rarely controlled by chemicals in established stands except in alfalfa because weeds reduce yield and quality of this superior forage species (Doll, 1994). Foxtails, quackgrass, Canada thistle, pigweed, lambsquarters, mustard, and volunteer grains compete aggressively with alfalfa in summer and reduce forage quality and acceptance. Winter annual weeds such as henbit and chickweed shade the crowns overwinter and reduce plant vigor in spring, weakening the stand and allowing summer weeds to increase. Some weeds have good forage quality but will still reduce yield (Marten and Andersen, 1975). An example is dandelion, which is an opportunist to become established and has upright leaves in thicker stands that extend more horizontally to remain very competitive as the alfalfa stand thins (Sheaffer and Wyse, 1982). However, dandelion populations in alfalfa are associated positively with populations of *Coleomegilla maculate*, an insect that feeds on pea aphids to reduce their damage to alfalfa (Harmon et al., 2000).

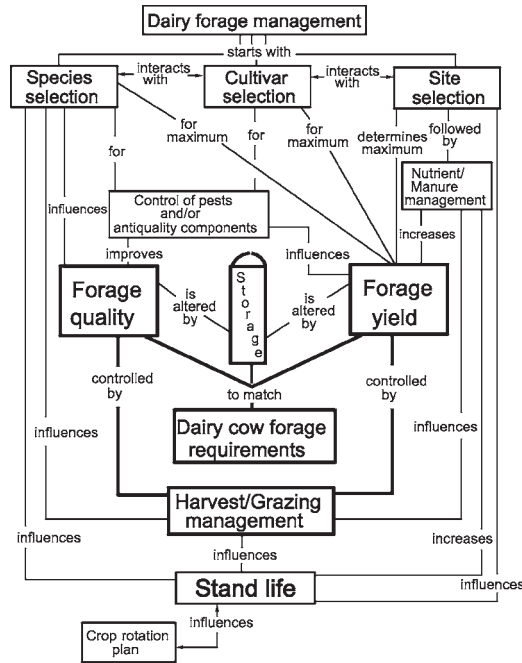
Weeds in either grass or legume monocultures can be effectively controlled with herbicides, while there are essentially no herbicides labeled for use on legume-grass mixtures. The primary and most cost-effective method of weed control in perennial forages is managing the forage crop to provide maximum competition against weeds. In the northern USA, weed encroachment in an established perennial forage stand is often only a side effect of a declining forage stand and can be used to help determine timing of crop rotation. Thinning



Weed management of haylands starts during establishment, after which plant competition is the major method used to reduce encroachment”



Recently alfalfa cultivars with glyphosate resistance have been made available by private industry.”



**FIGURE 4.11.** Major linkages in a dairy-forage system focused on management for economic production of quality forage and stand life to meet nutritional requirements of lactating cows. Note nutrient management has a major effect on yield whereas harvest management affects yield, quality, and stand life. From Cherney and Cherney (1993).

usually does not reach this stage in the first 2 or 3 yr, so weed control is usually not used for short rotations. Weeds tend to be more effective competitors in southern regions where longer stand durations are preferred.

Gaining maximum competition from forage crops begins with site selection, preferably one that has appropriate soil drainage, pH, and fertility for the forage crops involved (Fig. 4.11). Soil pH and soil fertility can be adjusted in advance of seeding to be optimal for the forages to be planted. Well-adapted cultivars should be selected. This is the most cost-effective method of weed control in established stands of perennial forages. Mowing is typically not very effective for reducing weed competition in established perennial forage stands not used as pastures. Weeds generally have a shorter development cycle than perennial forages, making it difficult to reduce seed production. Many perennial weeds require repeated mowing to weaken the plants, but this is not compatible

with good forage harvest management schemes. A vigorous, healthy stand with an aggressive harvest management for high-quality forage will be beneficial for weed control.

Recently alfalfa cultivars with glyphosate resistance have been made available by private industry. A small percentage of the individual plants in the cultivar will not be resistant because of the genetic nature of alfalfa, which does not allow pure lines to be developed like for annual crops. Even so, glyphosate-resistant cultivars can be an alternative tool for weed control during establishment of pure stands, and later to control weeds that increase during the life of the stand. Experiments in several states showed seeding-year yields were slightly lower at 6.7 kg ha<sup>-1</sup> than seeding rates of 11.2, 15.7, or 20.2 kg ha<sup>-1</sup> (Hall et al., 2010). Alfalfa plant density was similar, but more weed mass was in the control treatment without a commercial herbicide. Competition was the key control for the next year with little difference among control and herbicide treatments. Forage quality was not affected by the glyphosate cultivar or herbicide treatment. This suggested that lower seeding rates may be feasible with glyphosate-resistant cultivars.

In other short-term experiments, with seeding rates as low as 4.5 kg ha<sup>-1</sup> in Missouri, glyphosate gave more consistent weed control because of its broad spectrum and had little direct effect on yield or quality of glyphosate-resistant alfalfa (Bradley et al., 2010). Alternatively, a long-term study in Michigan considered potential for extending stand life by controlling weeds as the alfalfa stand thinned in a natural pattern from 236 to only 27 plants m<sup>-2</sup> over the period of 8 yr (Min et al., 2012). Forage quality was affected by cutting frequency but most years was not affected by weed removal by herbicide treatments. The stand thinned at a similar rate with and without herbicide treatment. Understanding economic value of using glyphosate-resistant cultivars in terms of lower seeding rates and extended stand longevity is warranted (Bradley et al., 2010).

Overall, Agricultural Experiment Stations and the Cooperative Extension Service have done a good job of determining harvest schedules

that optimize economic return and stand longevity for major forage crops in the state or region. This includes research on timing of first harvest, frequency of harvests, optimal stubble height left after harvest, timing and rates of fertilizer regimens, managing for drought and winter stress, and determining effects of major weeds, diseases, and insect pests. In most cases, however, research evaluations are focused primarily on the yield, quality, and persistence of major species harvested for use as livestock feed. Further, most studies were conducted on flat sites with average or better soils. Except for some studies on erosion control and nutrient use, there has been little research attention given to environmental conservation and provision of other ecosystem services.

Therefore, the question was addressed, “How much change occurs in economic returns when management goals are extended beyond yield, quality and persistence of monocultures or mixtures to incorporate the other purposes of the Practice Standard?” Focus was on those purposes associated with management decisions to improve the environment or provide more ecosystem services such as plant diversity and enhanced conditions for wildlife. Concurrently, issues of reduced production were considered while the forage serves as a soil nutrient uptake tool, improves control of insects, diseases, and weeds, and maintains or improves wildlife habitat.

#### **PURPOSE 6: MANAGE FORAGES TO MAINTAIN AND/OR IMPROVE WILDLIFE HABITAT**

Many options exist for landowners who need a stored forage supply but also want to provide habitat and food supplies for wildlife. Some US literature from the wildlife perspective supports alternative management practices, mainly time of cutting, and is usually focused on ground-nesting birds. Limited literature has caused several states to develop recommendations partly based on the combination of plant and wildlife research focused on food chains, nesting times, and desirable habitat. Minimal amounts of research are usually supplemented by intuition and experiential knowledge. This is clearly a stop-gap method, is usually focused on one or two wildlife species, and usually does not include effects on nonfocused wildlife

or determining rational balances between production economics and providing habitat or food supplies for wildlife.

#### **Alfalfa**

Many worms, insects, rodents, and other animals live in or are attracted to hay fields for some of much of their life cycle. The most studied situation is alfalfa that is being cut for quality hay or silage. California studies show alfalfa provides good protection and supports varied food sources, especially insects, for hundreds of species of songbirds, swallows, bats, and many types of migratory birds including waterfowl (Putnam et al., 2001). This includes more than 150 resident species of amphibians, birds, mammals, and reptiles. The high palatability of alfalfa, which makes it such a good dairy feed, also makes it desirable to many herbivores, including many species of insects, rodents, and grazing animals. It also provides protection and food for herbage consumers such as rabbits, voles, mice, and gophers. In turn, these birds and small mammals provide food for predators such as fox, hawks, and vultures.

In the southern USA, alfalfa is being evaluated for wildlife plantings based on its high N fixation, good forage quality, and desirable canopy structure (Ball, 2010). Hardy plants can be grown in the South with occasional cutting to support regrowth and young forage for deer, birds, and other wild animals. Ball indicates the value of alfalfa used by wildlife is almost certainly underestimated by most farmers and the public. Until a few years ago conservation plantings focused on food grains, mainly annuals, in recommended planting mixes for food and habitat. Advances in disease resistance and introduction of grazing-tolerant cultivars of alfalfa have improved potentials for large herbivores. High forage quality helps milk production and reproduction of deer and other small mammals. Ball (2010) also points out the vast number of insects that reside in alfalfa fields that provide support for birds and other animals in the food chain.

Thus, the alfalfa environment in many geographic regions supports a multiplicity of wildlife species in harmony with the growing canopy. The challenge, however, is that first harvest of alfalfa grown primarily for high yield



Many options exist for landowners who need a stored forage supply but also want to provide habitat and food supplies for wildlife.”

Wild turkeys do well within managed areas. NRCS photo.





Conservationist conducting a habitat survey for birds in Connecticut. NRCS photo by Paul Fusco.

of high-quality feed occurs at early flower stages which coincide with nesting periods of many wildlife species in the Midwest and eastern states. The main disrupter is close and frequent harvests that rapidly change the habitat and food chain. This situation has become a greater problem following major genetic increases in winter hardiness and plant persistence that has led to earlier and more frequent harvests during the growing season.

Research conducted several years ago in several Midwestern states, for example Leopold et al. (1943) in Wisconsin, Leedy and Hicks (1945) in Ohio, Baskett (1947) in Iowa, Trautman (1982) in South Dakota, and Warner (1981) in Illinois, pointed out first harvest of alfalfa destroys nests of ringnecked pheasants. In South Dakota the normal first cutting in mid-June killed 32% to 39% of the incubating hens and destroyed 86% to 91% of the nests (Trautman, 1982). In contrast, a more recent long-term

multistate evaluation including Illinois indicates if the trend toward earlier harvest of alfalfa continues, it will benefit pheasant, since first harvest will occur before the peak nesting period (Warner and Etter, 1989).

Researchers in South Dakota evaluated yellow-flowered alfalfa (falcata types), which has tall growth, lodging resistance, and flowers over a longer period of time than sativa types, until 1 July or later (Boe et al., 1988). It was hypothesized that late maturity of falcata would help farmers stagger harvest dates for production in semiarid areas where one or two-cut systems are common and improve success of ground-nesting birds, especially pheasants, that attract hunters to the state. Synthetics that included falcata genetics were high yielding when harvested in mid- to late July, but quality was lower even though falcata types tended to have better resistance to potato leafhopper. Regrowth of falcata types was less than that

of conventional cultivars and could be grazed. Although falcata types have superior winter hardiness, they need to have improved quality for both wildlife and harvested forage. The major deterrent to use of falcata types is very poor seed production.

Nesting water fowl were monitored in south-central North Dakota where about 57% of duck nests would hatch by 10 July, 78% by 20 July, and 85% by 25 July. Other evidence indicated later maturity and harvest would maintain habitat for several species of grassland songbirds, allowing them to fledge at least one brood (Berdahl et al., 2004).

### Other Forage Species

Other legumes are being considered for wildlife benefits, including native legumes, but little is known about their production and management. For example, native legumes such as wild bean are being evaluated in Texas and Oklahoma (Butler and Muir, 2010) for agronomic characters that need to be understood before there is further evaluation for wildlife benefits (Butler et al., 2006). Specific studies needed include rhizobia requirement, soil pH, P and K needs, forage and seed yield potentials, responses to cutting, and herbicide tolerance. These are critical since many of the native legumes have indeterminate flowering and seed pods that dehisce, which leads to poor seed harvest. The specific rhizobia also may be unknown or not available (Barker et al., Chapter 2, this volume)

All 15 native legumes evaluated in Missouri had higher protein and lower neutral detergent fiber concentrations than did switchgrass, big bluestem, and indiangrass (McGraw et al., 2004). Legumes were inoculated by use of soil from areas with dense plant populations. Based on forage yield, quality, and seed production, Illinois bundleflower had the greatest potential for use in mixtures with native warm-season grasses. In Kansas, Posler et al. (1993) evaluated yield and quality of binary mixtures of five native legumes and three native warm-season grasses. Addition of legumes increased yield and protein concentration of the mixture, but not digestibility. Once agronomic characteristics are known, legume-grass mixtures can be tested in management systems with potential to favor wildlife.

A modeling effort in Mississippi considered preferences of white-tailed deer for soil resources and forage quality (species not reported) (Jones et al., 2010). Principle component analysis showed deer abundance increased as soil fertility and forage quality increased, with these two variables contributing 58% of the variation in body mass and 52% in antler score. Further, based on general linear models the soil resource components explained 78% and 61% of the variation, respectively. Greater forage availability and quality likely provide a better nutritional plane for herbivores (Strickland and Demarais, 2008). Calcium may have also been important. Most studies on wildlife evaluate plant density and an estimate of quality without documenting the soil resource that likely has both direct and indirect effects on structure of habitat and quality of the food supply.

A detailed review of relationships between modern agricultural practices in Europe and decline in wildlife species gives insight to key principles (Wilson et al., 2005). The authors concluded that agricultural practices have negatively affected diversity of birds, mammals, arthropods and flowering plants. The major effect of intensification has been on crop structure that is now based on a few plant species. Forages are harvested more frequently or grazed more intensively; grain crops are shorter, but have dense structure after harvest due to N fertilization. The authors focused mainly on birds and indicate protection, food sources, and amount of intercepted solar insolation for temperature control of wildlife are critical.

In general, grazing is favored by many wildlife species over cutting because it leaves a heterogeneous sward of vegetation mosaics (Wilson et al., 2005). These swards, especially if somewhat sparse, have bare ground and seed abundance. Some birds depend on nearby trees or shrubs for protection. In one study 15 of the 20 key “farmland bird species” benefited more from shorter heterogeneous swards for foraging and detection of predators. Each bird species reacts differently, however, indicating one crop management system will not favor all. They concluded that structure should be emphasized in crop management with adjacent areas set aside to be managed for food supplies.



The main disrupter is close and frequent harvests that rapidly change the habitat and food chain.”



Wildlife biologists for most states in the USA have substantial research data for nesting dates, food sources, and desirable habitats for a range of bird species”

A similar conclusion was reached by Roth et al. (2005) in Wisconsin after their evaluation of a biomass harvest of switchgrass in August. Interestingly, they focused on the population of grassland birds the following year. Harvested plants had shorter vegetation and lower density the next year than did areas that were not harvested. The shorter areas were preferred by grassland birds whereas tall material was preferred by tall-grass bird species. They suggest it would be advantageous for bird populations to not harvest some field areas each year so they could provide habitat for a wider range of available structure and to increase local diversity of grassland birds.

Wildlife biologists for most states in the USA have substantial research data for nesting dates, food sources, and desirable habitats for a range of bird species (see Table 4.4). Thus, recommendations for forage harvest are based primarily on needs of wildlife, mostly on habitat associated with nesting times, with few data on concomitant influences on forage yield and quality. Several state conservation departments have published guidelines for farmers who desire forage species that are more compatible or can be managed as hay and silage crops in ways that are least disruptive to wildlife (e.g., Ochterski, 2006, in New York; Anon, 2010, in Pennsylvania; Anon., 2012, in Missouri).

General recommendations for hay harvests to support wildlife are usually based on birds and are quite similar to the representative one for nesting habits from Pennsylvania (Table 4.4), with emphasis on life cycles of prevalent wildlife for each particular state. Using Pennsylvania recommendations as a general template, the emphases on species and preferred harvest management include the following:

1. Cutting some forage grasses or legumes for hay or silage at the peak of production may be compatible with habitat value of some wildlife, but the best mowing times and heights depend on forage species and desired wildlife.
2. Some areas of forage legumes should be cut very early, before nesting begins, or late, after nesting ends. These mowing strategies may be beneficial since most forage is harvested in a timely way for forage value, while other areas are left to favor wildlife.
3. Mowing cool-season grasses at the boot stage in May minimizes effects of mowing on most nesting wildlife by allowing some regrowth prior to peak nesting season (June–July). Sensitive periods for major wildlife have been defined (see Table 4.4 for Pennsylvania).
4. Cutting cool-season grasses late, for example, first cut during June and July, may destroy nests and kill young wildlife, and hay quality will be lower than when cut at early heading.
5. Native warm-season grasses (e.g., indiagrass, switchgrass, big bluestem, Eastern gamagrass) mature later than most cool-season grasses (Fig. 4.10) and should be cut during the early seedhead stage, when their nutritional yield is greatest. These grasses usually have peak growth during mid- to late summer after the main nesting periods. Thus, cutting time of warm-season grasses is usually less of an issue for wildlife but should occur between 1 and 15 Aug.
6. Native warm-season grasses provide excellent food and year-round cover for wildlife. Forage should be cut to leave 25 cm of stubble, and subsequent use should allow regrowth of 25–30 cm before the first killing frost to provide adequate winter cover for grassland wildlife (Fig. 4.2. in Nebraska).
7. Occasional disturbance from mowing, burning, spraying, or disking is needed to maintain a native grass field. Without disturbances, succession will cause the grassland to be replaced by woody vegetation causing wildlife that require grassland or meadow habitat to be replaced by more common woodland wildlife.
8. Mowing to control “weeds” may not be beneficial for some wildlife. Controlling plants such as thistles is important, but many “weeds” such as nettles, foxtail, and ragweed are palatable to wildlife or attract insects needed to meet diet requirements of many bird species. The goal is to provide a balance between volunteer forbs (weeds) and other desirable forage plants to provide diversity.
9. Field borders are valuable to wildlife and can be simulated by squaring off the

inner portion of irregular-shaped fields for regular harvests. Delaying mowing the angled spaces until August or leaving a 10-m border along wooded areas or fence rows helps provide habitat and food. These outer areas are often less productive for hay, dry slowly, or have fallen branches that can damage haying equipment.

### Types of Mowing Patterns

Many state agencies that are responsible for wildlife conservation recommend considering three main types of mowing: 1) Block mowing involves dividing fields into three or four blocks that are mowed on a rotational schedule. This allows different growth stages of forage to exist within a large field. 2) Strip mowing involves dividing a field into strips with fixed or variable widths. A proportion of strips should be harvested each year, but switched annually such that a given strip is not mowed in consecutive years. 3) Random-pattern mowing involves dividing a field into several irregularly shaped patterns assigned to provide cut and not-cut vegetation cover. Each area should be harvested rotationally over years to have a 3–5 yr harvest cycle, primarily to reduce encroachment of woody vegetation.

Regardless of the type or pattern used for mowing, the not-mowed areas or strips should be at least 30 m wide and consist of at least 0.25 ha. Blocks or strips that are too small or too narrow can serve as “habitat sinks,” making it easier for predators to hunt the small animals that the land manager desires as outcomes from the habitat management objectives.

Most of these practices have not been researched using established methods to gain supporting data for the forage resource or other ecosystem services, yet they can be considered as “logical uses” of the technology based on life cycles of forage species, desirable wildlife species, food chains, and predators. This focus tends to promote managing the forage resource less intensively, which may be acceptable to landowners who are willing to sacrifice income to accommodate increased plant and wildlife diversity.

### Alternatives to Mowing

An acceptable alternative to mowing is spot spraying grass stands with selective herbicides

**TABLE 4.4.** Common nesting periods in Pennsylvania for a range of wildlife species (Anon., 2010).

Wildlife:	Nesting period
White-tailed deer	15 May to 15 July
Eastern cottontail rabbit	1 Feb. to 30 Sept.
Wild turkey	15 April to 31 July
Bobwhite quail	15 April to 31 July
Ring-necked pheasant	15 April to 30 June
<b>Grassland songbirds:</b>	
Eastern meadowlark	15 May to 31 July
Grasshopper sparrow	1 June to 15 Aug.
Field sparrow	15 May to 15 Aug.
Bobolink	15 May to 30 June
Dickcissel	1 June to 31 July

to control noxious weeds and woody plant invasion. This is most critical during the establishment period of grass stands when competition is low and outbreaks can be treated at first detection. Use of selective herbicides before and after grass/legume plantings helps control noxious weeds to establish a successful stand, but there are few herbicides for grass/legume fields. Random or strip spraying may be performed throughout the year taking care to not damage the established forage stand. Herbicide spraying can be used on random patches or fixed strips within a field.

Strip or rotational disking is a simple, effective, and inexpensive tool to manage wildlife habitat. In strip disking, a disk or harrow is used to create ground disturbance in strips to reduce natural succession by breaking up grassy vegetation. Disking opens up grass stands, reduces thick mats of thatch, stimulates germination of seed-producing plants, and increases insect populations as a wildlife food source. But even light tillage will increase loss of organic carbon from the soil.

Prescribed burning is an alternative to mowing, especially when managing many larger fields of native perennial warm-season grasses. Controlled fire using approved methods and safety precautions sets back natural succession and releases nutrients to stimulate growth of valuable grasses and legumes. Prescribed



Few US studies have evaluated both forage and wildlife in the same experiment.”

burning is less expensive and time consuming than mowing and produces many wildlife and forage benefits. However, prescribed burning requires careful planning and controlled conditions to be an effective management tool. An early season burn works well for perennial warm-season grasses. Improved technologies are needed, especially those addressing timing of burning, which is not well defined for cool-season grasses.

Few US studies have evaluated both forage and wildlife in the same experiment. In Quebec, 20% of North American wood turtles in a mixed-species hayfield were killed by mechanical harvest of first growth with a disc mower (Saumure et al., 2007). In addition, 90% of adults that survived and 57% of juveniles were mutilated. The turtles leave the grassland area before second harvest. They recommend that cutting height of disc mowers be increased to 100 mm since most turtles are < 87 mm high. Sickle-bar mowers cause less death and damage since sickle guards tend to move turtles away from the sickle, albeit with some injury. The authors cite data that a higher cutting height would also reduce wear on the harvester, result in higher quality forage with less stem, and provide more rapid regrowth. Also, the taller stubble would reduce runoff and soil erosion. Understanding interactions among these socioeconomic values in the same experiment is needed (Warner and Brady, 1996).

More emphasis has been placed on assessment of wildlife needs in areas with large tracts of public lands, where grazing predominates. On most public lands, and many private lands, there is direct competition between livestock and wildlife (Cory and Martin, 1985). Loomis et al. (1989) derived a demand curve using a regional travel cost model to statistically estimate marginal value of land for either livestock or wildlife use. Estimates of economic values of forage for elk and deer in Idaho were generated with this method. Loomis et al. found that marginal forage values of deer and elk sometimes exceed livestock forage values. They suggested that wildlife habitat issues should play a major role in determining seasons of use and optimal stocking levels for ranges. Similar methods could be used to assess the relative cost effectiveness of modifying forage harvest regimes to benefit wildlife.

In Nova Scotia a holistic approach to ecosystem services involved fledgling success of ground-nesting birds and forage quality of first harvest of a mixture of timothy, meadow foxtail, several bluegrasses, and reed canarygrass. Delaying cutting from 20 June to 1 July increased fledgling from 0 up to 20% for bobolink, 56% for savannah sparrow, and 44% for Nelson's sharp-tailed sparrow. Delaying cutting to 7 July allowed maximum fledgling rates for all species. Protein concentration of forage on 20 June had decreased by 2.1 percentage units by 1 July and by 3.5 percentage units by 7 July, whereas acid detergent fiber gradually increased. Calcium and phosphorus remained rather constant. They concluded forage quality decreased when cutting was delayed but was still sufficient for many classes of livestock. Unfortunately they did not report changes in forage yields that would help in economic assessments.

In summary, despite growing public interest and implied responsibility of land owners to support wildlife, there are very few data for specific practices. In most cases the practice that would support one or a few species of wildlife could be to the detriment of other species. The literature tends to show habitat may be the most critical factor regarding harvest management compared with food supplies (Wilson et al., 2005). Timing of harvest to avoid the nesting period, especially the first harvest each year, is critical for most grassland birds. Since landowner goals are a major part of selection of conservation practices to be implemented, landowners should be aware of effects of a management practice on various types or forms of desired wildlife. In some cases, managing stubble height for water management and erosion control may be beneficial to some wildlife and detrimental to other types (Sollenberger et al., Chapter 3, this volume). An overriding challenge is the need to evaluate forage production issues and wildlife systems in the same experiment. Overall, there will be no easy answers; wildlife species that are most desired need to be identified early and given appropriate priority in management decisions.

Fortunately most states have rather good data on life cycles, especially nesting habits, of birds that frequent hayfields in the region. That information, and needs for structure and

habitat at certain times of the year, e.g., winter, should allow wildlife biologists, agronomists, and animal scientists to develop experiments to validate the observations. Soils should not be overlooked since production capacity and environmental stability, especially on low-productivity and sloping sites, may be key areas where multiple functions of haylands are best accomplished. Above all, one or more common denominators for forage value and ecosystem services need to be developed that allow objective as well as subjective assessments of desired outcomes from implementation of a conservation practice.

### ACHIEVING MULTIPLE GOALS BY FORAGE HARVEST MANAGEMENT

There is movement among the public and policy makers that forages and other land management systems need to achieve multiple goals that contribute to sustainability and resilience of ecosystems and efficient use of natural resources. This context goes well beyond production and extends to broader and long-term food system goals. In this case, roles and management of forages for hay and silage play a critical part in the matrix of activities on the landscape that help facilitate these goals. Future practice standards will need to address these multiple objectives as they grow in importance, and as new research points the way for solutions and compromises among competitive goals. This requires scaling up to whole-farm systems, and beyond, to integrate the land used for hay and silage production into the larger picture involving economic returns, conservation of resources, and providing other services for the public.

#### Nutrient Balance for Livestock

Nutrient balance within a livestock farm is essential for sustainable, economically feasible livestock production where hay and silage are often important components of the system. Home-grown forages benefit nutrient balance by removing excess nutrients from the soil and serving as a repository for manures to minimize import of nutrients from off-farm. Grazing can be utilized as an efficient forage harvesting system; however, most farms require some forage be harvested and stored for later use. Harvest management controls both forage yield and quality and has a strong influence on

stand life (Fig. 4.11). It also affects outputs of ecosystem services such as water quality and wildlife diversity.

Regardless of harvest time, two primary methods of storage are silage (Buxton et al., 2003) and dry hay (Hall et al., 2007). Management prior to harvest is similar for forage that is to be stored as silage or hay, but harvest and storage losses of nutrients are greatly affected by forage composition and the specific details of the harvest and storage processes (Fig. 4.9). Agricultural Experiment Stations have developed good management recommendations for harvest of hay or silage for major forage species and popular mixtures that are adapted and used in that respective state. Invariably recommendations are based on basic principles of forage management and are supported by field research that is often published in semitechnical outlets for practitioners. Guidelines for reducing storage losses are not common among all states, yet these losses affect feed quantity and quality in negative ways and need to be managed to minimize losses.

#### Forage Contributions to Precision Feed Management

Recently attempts have been made to combine environmental and economic sustainability with feeding management, referred to as either precision feeding or precision feed management (Ghebremichael et al., 2007). The two primary concepts involved are 1) use diets that maximize forage and homegrown feeds diets and 2) ensure nutrient contents for optimum production without overfeeding. Goals are to 1) improve nutrient efficiency and economic returns, 2) optimize the balance between purchased feed nutrient imports and on-farm feed production, and 3) minimize nutrient overfeeding and nutrient excretion (Cerosaletti and Dewing, 2008) (Fig. 4.11). Nutrients must be fed slightly above requirements to accommodate daily variations, but any excess N or P in the diet is excreted by the animal.

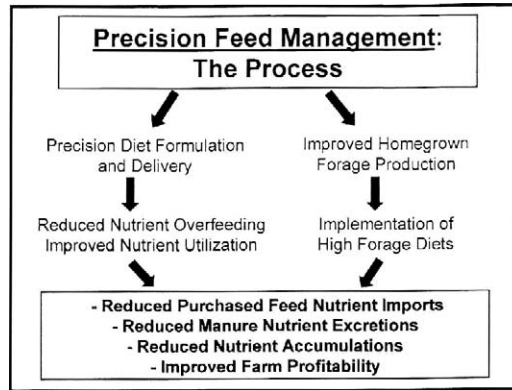
Precision feeding is based on measurable characteristics and requires monitoring and effective record keeping (Fig. 4.12). A cropping plan is designed to match available land resources, output needs of the farm, and the farm's conservation plan. Available machinery, labor, and storage facilities are evaluated to



Recently attempts have been made to combine environmental and economic sustainability with feeding management”



monitoring and record keeping involved with precision feed management will minimize nutrient losses in the system.”



**FIGURE 4.12.** Precision feed management helps balance nutrient supply from forages to prevent overfeeding and to maximize use of on-farm forages in the diet. The end result is high efficiency of forage use and provision of areas where manures can be recycled on the farm. From Cerosaletti and Dewing (2008).

determine if the farm has the capacity to harvest the desired quantity and quality of forage in a timely manner and allow for proper storage and allocation of feeds (see next section on modeling). Benchmarks for forages to be successful with dairy cattle (Cerosaletti and Dewing, 2008) are the following:

1. Neutral detergent fiber intake > 0.9% of body weight
2. Forage goal > 60% of the diet dry matter
3. Homegrown feed goal > 60% of the diet
4. Phosphorus in ration < 105% of animal P requirement
5. Crude protein in diet < 16.5%
6. Urea N in milk produced, 8–12 mg dL<sup>-1</sup>
7. Calving interval < 13 months
8. Less than 5% of cows die or culled at < 60 days in milk.

Compared to conventional ways, precision feeding of lactating dairy cows reduced P concentrations in manure by 33%, showing potential for a major impact on P imports in watersheds where dairy farming is the primary agricultural activity (Cerosaletti et al., 2004). A primary requirement for precision feed management is harvest of high-quality forage, coupled with nutrient management (Cherney and Kallenbach, 2007). Hay and haylage quality goals for grasses are approximately 50–55% NDF and 38–40% NDF for alfalfa.

Goals for alfalfa-grass mixtures are intermediate and a function of the proportion of grass in the stand (Cherney et al., 2006). Nutrient management is an integral component of this process, leading to high yields of highly digestible forage that is free of toxins and severe mineral imbalances.

Forage mixtures (e.g., alfalfa-grass) can provide high-quality forage for dairy cattle while eliminating or minimizing fertilizer N inputs and maximizing protection from both runoff and leaching. Grass species that are sod forming with robust root systems, such as reed canarygrass, will minimize runoff. Species such as timothy, with much lower apparent N recovery (ANR) and lower CP content, require more supplemental N in cattle diets and should be avoided. Strict guidelines for manure applications on forage crops will minimize environmental concerns and animal pathogen issues. Partial incorporation of manure on forage lands will minimize surface runoff risk. Increased number of harvests will increase ANR and increase forage quality for precision feed management. The monitoring and record keeping involved with precision feed management will minimize nutrient losses in the system. A harvest management that provides high-quality forage is essential.

Special attempts need to be added to precision feed management strategies on dairy farms to meet the purposes and criteria. Environmental and wildlife goals implied in conservation Standard Code 511 should include practices for fields harvested for hay and/or silage. Each field is expected to contribute these services and be managed to realize them. The flexible harvest/grazing management strategy can be adjusted to meet multiple objectives including soil erosion, manure management, other nutrient management, water quality, and wildlife. Each of these needs a balance sheet or diagram to show the various interactions that could occur due to the management system employed. This would also allow the planner to understand if yield, quality, or stand life would be the major factor altered. Thus, there is a need for modeling efforts to help understand the interactions. Research efforts in combination with other data such as rainfall, temperature, and soil properties are critical (Nelson, Chapter 6, this volume).

Similar guidelines for having successful whole farm systems have been considered for beef production (Allen et al., 1992, 2000; Allen and Collins, 2003). Components for beef cattle differ from those for dairy cattle since grazing is a larger part of forage use (Sanderson et al., Chapter 1, this volume), but some hay or silage is required causing the need for another set of data inputs for integration of practices and desired outcomes. For example, compared with a dairy farm, primary forage and livestock breeds on a beef farm are different; pastures are the dominant feed source, priority for high forage quality may be lower, the soil resource may have lower inherent yield potential, the primary focus is on weight gain, most manure is deposited nonuniformly on pastures, and areas used for hay or silage production may also be grazed part of the year. Further, provisions of desired ecosystem outputs by the beef producer may involve priorities that differ from those of dairy farmers.

These interactions among different goals and the methods to achieve them indicate a need for broad education over a range of outputs and strategies. Once goals are defined, application of models that evaluate interactions among major inputs and outputs would be valuable. Education programs should be put into place to help landowners prioritize desired outputs and ways to best achieve them. This should then be followed with periodic monitoring to determine if the practice is working and to assist the landowner apply adaptive management practices to sustain effectiveness of the installed practice.

### Use of Comprehensive Models

Modeling was introduced to forage management several years ago with the primary focus on a single component of the entire system even though it had limitations (Debertin and Pagoulatos, 1985). They used a model to focus on alfalfa and crop management within the context of a total farm plan for west-central Kentucky when alfalfa was harvested 3, 4, or 5 times annually. They found the five-harvest system competed with crop production for time and equipment at the desired planting period, especially in a wheat-soybean double crop situation, which could lead to harvest delay and reduced forage quality. It was clear that the best management for alfalfa could not be realized

when the entire farm was considered. In fact, in some scenarios, due to challenges with time management, some of the forage could not be harvested. They found tradeoffs would be necessary to achieve most of the goals.

More recently Rotz et al. (1989) have led efforts to develop models that integrate numerous aspects of forage management on a whole farm as a comprehensive system. Examples include manure application methods (Rotz et al., 2011), carbon footprints (Rotz et al., 2010), greenhouse gas emissions (Chianese et al., 2009), and phosphorus losses (Sedorovich et al., 2007). This research also shows it may be very difficult to achieve and maintain high forage productivity and quality simultaneously with needs of other enterprises on the farm. Therefore, these models allow some economic analyses of competing enterprises such as row crops within a whole farm comparison. Computer capabilities and better programs have added to potentials of models for planning and evaluation of conservation practices. Integrated crop-livestock systems for the future may occur within a farm and more likely among farms that occupy watersheds or other basal units. These complex systems will require sophisticated computer programs to enhance both profitability and environmental sustainability (Russelle et al., 2007).

### CONCLUSIONS

For assessment of each purpose the various criteria and goals were listed and then evaluated according to amount and comprehensiveness of published data. In some cases there are ample data for national standards and thus summarized as being adequate (Table 4.1). In other cases there were few or no data available, in which case the summation indicates a specific need and in some cases for specific types of data. Some criteria had intermediate levels of support, and the strengths and deficiencies were pointed out. Overall, the evaluation team felt most production purposes on major species were supported strongly by the published research data. At the same time it was recognized and noted that most local applications of basic principles were developed from local experiments that were published in nonrefereed publications, yet were consistent with the basic literature.



Once goals are defined, application of models that evaluate interactions among major inputs and outputs would be valuable.”



Assessing goals is even more critical during monitoring of the installed practice to ensure it is working as planned.”

In all cases it was clear that the published data would not answer all the questions that could arise as the field site was evaluated and a structure or practice was proposed and implemented. While species differences were apparent, the most notable factor was harvest practices to address environmental concerns such as soil erosion, water quality, and climate change. In these cases, the experience and intuition of the professional would need to play a larger role by adjusting for local soils, climates, and the local public interests. There was very little research on the roles of harvest management on wildlife, except for nesting patterns, and often the research was on success of only the target species. Little data were presented on habitat, competition among wildlife for food sources, and effects of management on predators. Comprehensive, large-scale research studies utilizing diverse scientists are needed to obtain the correct data to fully evaluate the ecosystem and its outputs.

More technical understanding can play a large role in evaluation and planning even if research is not available. Specialization is needed for evaluation and implementing practices, but broad education is needed to evaluate how the practice will affect the physical environment and local wildlife. Discussions are needed among scientists and professionals to discuss the implications of the program goals based on simple studies and experience-based knowledge, and the landowner needs to be involved. Assessing goals is even more critical during monitoring of the installed practice to ensure it is working as planned. Some results may be achieved quickly, while other outcomes may take several years to become fully credible. Unfortunately nearly all the research is short term, whereas most conservation practices should be long term and have measurable outcomes. Monitoring will be a great asset to the understanding of the practice and what happens over time after the practice is installed (Easton et al., 2008).

There is a gap in the research between those interested in production and those scientists interested in environmental issues or wildlife issues. Too many research papers focus on one aspect with little consideration of the others. For example, we saw many papers addressing major forage management issues with good

plant data without enough environmental or wildlife data to document treatment effects. Conversely, there were detailed studies of bird populations and nesting without quantitative data to describe the forage and soil condition. Incentives are needed to ensure the research is comprehensive and of sufficient duration to fully document the responses.

Further, the management effects appear to be somewhat specific relative to optimal environmental results and/or wildlife results. There are other interactions that may offset environmental and wildlife goals of the landowner. In that sense, there is a need to construct practical models to evaluate the interactions and determine the cost-benefit relationships of competing outcomes. Clearly the landowners may differ in their expected “returns” from implementing a conservation practice. These are dealt with in more detail in the synthesis chapter (Nelson, Chapter 6, this volume).

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## CHAPTER

# 5

# Nutrient Management on Pastures and Haylands

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...nutrient management  
of pastures and  
haylands has enormous  
production, economic,  
and environmental  
implications”

# Nutrient Management on Pastures and Haylands

# 5

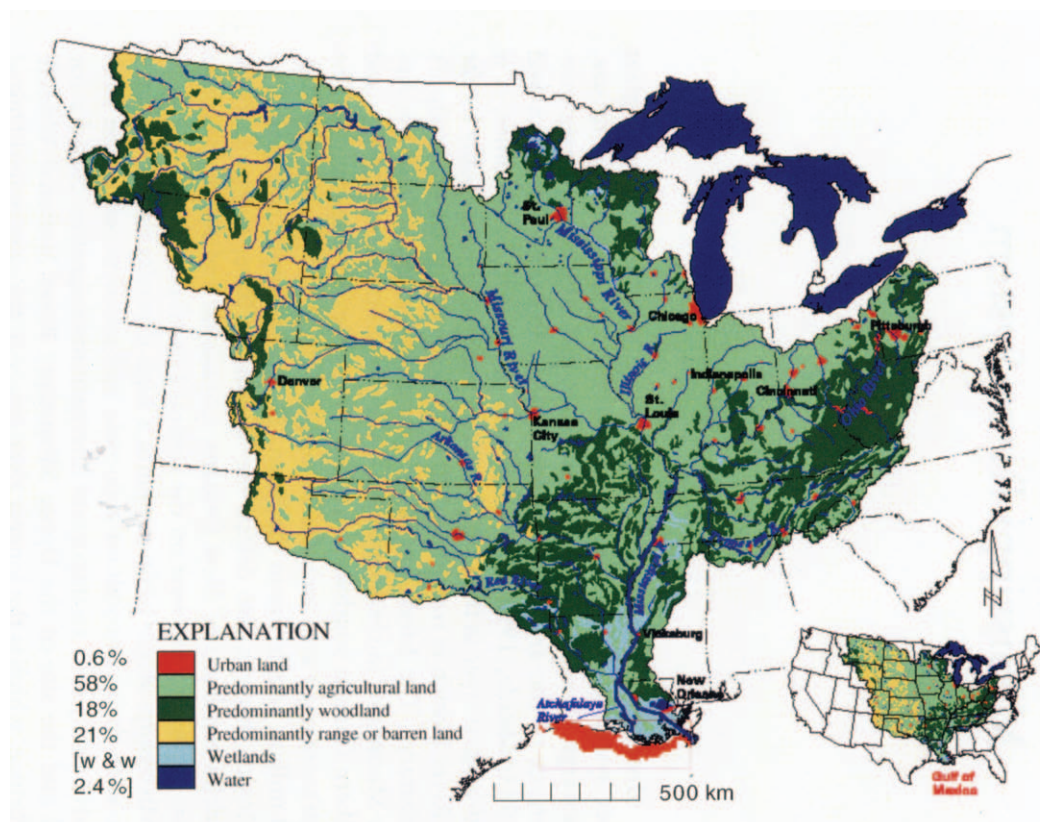
C. Wesley Wood, Philip A. Moore, Brad C. Joern, Randall D. Jackson, and Miguel L. Cabrera

## INTRODUCTION

Judicious use of nutrients is critical for management of the 74 Mha of U.S. pasture and haylands (Fig. 1.1) owing to its agronomic, economic, and environmental implications. The primary goal of nutrient management is to promote biomass productivity that provides profit for producers while minimizing negative environmental impacts. Additional goals include improvement of soil quality, increased soil carbon (C) sequestration, and providing important ecosystem services.

The scientific literature is replete with examples of forage response to fertilization that increase agronomic yield. However, when fertilizer costs are considered, maximum forage yields are often not in the best interest of producers; aiming for maximum economic yield with less nutrient inputs is desired. This is especially true in today's economic climate because fertilizer costs, especially nitrogen (N), are directly tied to energy costs.

Although production and producer profit are important, protecting the quality of soil, water, and air resources is imperative



**FIGURE 5.1.** Mississippi River drainage basin showing major tributaries and the general location of the hypoxic zone south of New Orleans in midsummer, 1999. Reprinted with permission from Goolsby and Battagli, 2000.



Proper nutrient management on pastures and haylands allows for healthy aquatic ecosystems.

to sustain the human race. The public has increased interest in having agricultural land provide ecosystem services like wildlife and plant diversity. According to the 2004 national water quality inventory report to Congress, the U.S. Environmental Protection Agency (USEPA) reported nearly 44% of U.S. rivers and streams; 64% of lakes, ponds, and reservoirs; and 30% of bays and estuaries waters are too impaired to meet one or more of their designated uses (USEPA, 2009). The report implied that agriculture negatively affected 38% of impaired rivers and streams; 16% of impaired lakes, ponds, and reservoirs; and 10% of impaired bays and estuaries. Nutrients were specifically listed as a cause of impairment for approximately 16% of impaired river and stream banks, 19% of impaired lake areas, and 14% of impaired estuary areas.

Pasture and haylands comprise 6% of U.S. lands (Fig. 1.2), most of which are in the Mississippi River Basin (Fig. 5.1), and thus their management has a large potential to impact environmental quality in the central USA. Nutrient runoff from the Mississippi Atchafalaya River Basins (MARB) (Fig. 5.1) produces the second largest coastal hypoxic zone in the world (Rabalais et al., 2002), which is detrimental to commercial and sport fisheries in the northern Gulf of Mexico. Although attention has been focused on losses of N from row crops (National Research Council [NRC], 2008), recent evidence suggests animal manure from pastureland contributes nearly as much P as row crops to the Gulf (Alexander et al., 2008). Proper nutrient management on U.S. pasture and haylands can help reduce hypoxic conditions in the Gulf of Mexico and other U.S. coastal zones.

Nutrient management affects important soil–atmospheric interactions. Processes that remove and store carbon dioxide (CO<sub>2</sub>) from the atmosphere and/or retard release of CO<sub>2</sub>, methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) to the atmosphere can help mitigate global climate change. Soil organic matter contains the largest terrestrial pool of C (Lal, 2004), and soils can be managed to sequester greater amounts of C, which improves soil quality in addition to lowering CO<sub>2</sub> content of the atmosphere. Nutrient management exerts control over sequestration of soil C under pasture and haylands via its influence on net primary productivity. Moreover, N management directly affects amount of N<sub>2</sub>O emissions from pasture and haylands. Lastly, nutrient management influences ammonia (NH<sub>3</sub>) volatilization from soils, which has important N-use efficiency, air quality, and ecological implications.

It is clear that nutrient management of pastures and haylands has enormous production, economic, and environmental implications. Thus, it is imperative that national policy on nutrient management as outlined by NRCS in Practice Standard 590 be supported by science and implemented. In this synthesis of U.S. scientific literature we ask the question “Does the scientific literature on nutrient management of pasture and hayland support the purported benefits outlined in Practice Standard 590?” Table 5.1 shows these purported benefits, the criteria used to assess the benefits, and the relative strength of research support for each criterion.

To assist in determining the scientific underpinning of the above benefits we downloaded the Conservation Physical Practices Effects (CPPE) matrix from the NRCS website and considered the hypothesized responses relative to the NRCS Nutrient Management Practice Standard (590) (Table 5.2). We bound our literature synthesis to managed pastures used for grazing or fields used for hay production. We searched for U.S. literature addressing nutrient inputs to pastures/haylands and practices designed to retain nutrients in these agroecosystems.

## BUDGET AND SUPPLY OF NUTRIENTS

Most grassland soils in the USA require nutrient additions to obtain optimum forage production and maintain desired plant species. Nutrient management in grasslands begins with budgeting nutrients based on the difference between the amounts of nutrients expected to be taken up by forage and the amounts made available within the soil. The difference is used to estimate the rates of nutrients to be supplied. Fertilizer recommendations developed by research at land grant universities are used almost exclusively to determine fertilizer rates to apply, although evidence from row crops suggests that these recommendations lead to overapplication of nutrients. This may also be the case with pastures.

Nutrient supply is only part of the picture—factors affecting forage uptake of applied nutrients (yield) are equally important, as it is the balance between supply and uptake that determines the potential for nutrient losses. Grazing and grazing management can affect the rate of forage growth, hence the extent of nutrient uptake and the potential for loss. And grazing animals recycle nutrients to the pasture and need to be considered. Once application rates are determined, decisions regarding source, timing, and placement method are needed to develop optimum nutrient management strategies. These strategies are commonly reported in land-grant university fertilizer recommendation bulletins. Source and placement may be generalized for most grasslands, but timing is specific to the species grown. Most nutrient additions should be made just before the forage starts rapid growth.

In addition to affecting forage production, decisions about nutrient source, timing, and placement affect physical, chemical, and biological conditions of the soil. They also affect air and water quality and atmospheric concentrations of greenhouse gases. Therefore, nutrient management decisions should include these multiple goals. In this section, we first review information related to budgeting and supplying nutrients to grasslands, followed by a scientific assessment of the nutrient management criteria listed in Code 590.



...nutrient management in grasslands begins with budgeting nutrients”

**TABLE 5.1.** Purposes of the Nutrient Management Practice Standard (Code 590) and criteria for assessing achievement of the purposes.

Purposes of the practice standard	Criteria for assessing achievement of the purpose	Support by the literature
<b>Budget and supply nutrients for plant production</b>	by developing a nutrient management budget using all potential sources of nutrients, including crop residues, legume credits, and irrigation water	Strong support for hayland, but need manure credits for pastures and research on phytoavailability.
	by establishing realistic yield goals based on soil productivity information, historical yield data, climate, management, and local research	Moderate support, more research needed on lower quality land sites.
	by specifying the source, amount, timing, and method of applying nutrients to each yield goal while minimizing movement of nutrients and other potential contaminants to surface or ground waters	Strong support for application ahead of growth, more research needed for offseason applications.
	by restricting direct application of nutrients to established minimum setbacks (e.g., sinkholes, wells, gullies, surface inlets, or rapidly permeable soil areas)	Strong support, but mainly based intuitively from other studies. More research needed for pastures and haylands.
	address the amount of nutrients lost to erosion, runoff, drainage, and irrigation	Strong support that this is critical, but need more soils and sites, perhaps models.
	applications be based on current soil (within 5 yr) and tissue test results according to land grant university guidance	Moderate support, current soil tests do not report P or N indices.
<b>Properly utilize manure or organic by-products as a plant nutrient source.</b>	by reducing animal stress and death from toxic or poisonous plants	Moderate support, but not a major problem in humid areas.
	by improving and maintaining plant health and productivity	Strong support, except on roles of organic by-products.
	by basing management on target levels of forage utilization or stubble height as a tool to help ensure goals are met	Moderate support showing principles; little on specific management practices.
	by locating of feeding, watering, and handling facilities to improve animal distribution	Strong support that would benefit from quantitative models to better define.
<b>Minimize agricultural nonpoint source pollution of surface and ground water resources.</b>	by improving or maintaining riparian and watershed function	Moderate support, research needed on more soils and sites.
	by minimizing deposition or flow of animal wastes into water bodies	Strong support, but would benefit from models.
	by minimizing animal effects on stream bank stability	Strong support.
	by providing adequate litter, ground cover and plant density to maintain or improve infiltration capacity of the vegetation	Strong support in concept, but responses need to be quantified for a range of soils and sites.
	by providing ground cover and plant density to maintain or improve filtering capacity of the vegetation	Strong support, but responses need to be quantified for a range of species and mixtures.
	by minimizing concentrated livestock areas, trailing, and trampling to reduce soil compaction, excess runoff, and erosion	Strong support and a range of practices to minimize soil damage, but few to restore soil condition.

TABLE 5.1. continued.

Purposes of the practice standard	Criteria for assessing achievement of the purpose	Support by the literature
<b>Protect air quality by reducing nitrogen emissions (ammonia and NO<sub>x</sub> compounds) and formation of atmospheric particulates.</b>	by reducing accelerated soil erosion	Strong support, would benefit from use of models.
	by minimizing concentrated livestock areas to enhance nutrient distribution and improve ground cover	Strong support, but needs to be integrated with plants and their growth habits.
	by improving carbon sequestration in biomass and soils	Strong support, would benefit from use of models to quantify relationships.
	by application of soil nutrients according to soil test to improve or maintain plant vigor	Strong support for most monocultures, need more research on mixtures.
<b>Maintain or improve physical, chemical, and biological condition of the soil.</b>	by applying and managing nutrients in a manner that maintains or improves the physical, chemical, and biological condition of the soil	Strong support intuitively based on annual crops, but needs verification using long-term perennials.
	by minimizing the use of nutrient sources with high salt content unless provisions are made to leach salts below the crop root zone	Strong support, but it does not appear to be a problem unless excess rates applied.
	by not applying nutrients when the potential for soil compaction and rutting is high	No support, research needed because perennials can become compacted, but are not tilled.

## Nitrogen

Rates of fertilizer N applications to grasslands depend on N uptake capacity of the forage and N made available within the soil. Nitrogen uptake of forages varies depending on plant species, soil characteristics, and environmental conditions. Annual N uptake of a mixture of smooth brome grass (scientific names of all plant species used in this chapter are listed in Appendix III) and alfalfa ranged from 90 to 211 kg N ha<sup>-1</sup>, depending on amount of fertilizer N added (Nuttall, 1980). Annual N removal in New York was 241 kg N ha<sup>-1</sup> for tall fescue and 205 kg N ha<sup>-1</sup> for orchardgrass (Cherney et al., 2002). In Texas, annual N uptake of 'Coastal' bermudagrass fertilized with ammonium nitrate ranged from 121 to 409 kg N ha<sup>-1</sup> depending on N rate used and environmental conditions (Silveira et al., 2007).

In natural systems like permanent pastures, available N for forage uptake is derived from that supplied from mineralization of soil organic matter and plant residues, grazing animal excreta, precipitation, and biological N<sub>2</sub> fixation. Nitrogen mineralized from

soil organic matter and plant residues may range from 40 to 230 kg N ha<sup>-1</sup> yr<sup>-1</sup> and is positively related to soil organic matter content, residue composition and favorable environmental conditions (Hopkins et al., 1990; Hassink, 1995). In comparison, N derived from deposited animal excreta can be as high as 1200 kg N ha<sup>-1</sup> in concentrated areas of deposition. This application rate is well in excess of potential forage uptake and can lead to N losses to air and water, although these hot spots of N loss may be distributed widely and comprise only a small percentage of the pasture area. The N received annually in precipitation usually ranges from 3 to 10 kg N ha<sup>-1</sup> (Whitehead, 1995), and biological N<sub>2</sub> fixation can supply as much as 400–650 kg N ha<sup>-1</sup> annually (Ledgard and Giller, 1995; Trott et al., 2004), although typical values range from 27 to 141 kg N ha<sup>-1</sup> (Yang et al., 2010).

Several indices have been developed to evaluate potential N mineralization during a growing season from soil organic matter (Schomberg et al., 2009), but currently there is no method to obtain an accurate estimate. The amounts of N mineralized from soil organic matter

**TABLE 5.2.** Conservation Physical Practices Effects (U.S. Department of Agriculture–Natural Resources Conservation Service [USDA–NRCS], 2009) on pastures and haylands associated with the NRCS Nutrient Management Practice Standard (Code 590).

Variable	Effect	Rationale
<b>Plant selection or condition</b>		
Plants not adapted or suited	Slight to substantial improvement	Nutrients and soil amendments are optimized to enhance suited and desired species.
Productivity, health, and vigor	Slight to substantial improvement	Nutrients and soil amendments are optimized to enhance health and vigor of desired species.
Forage quality and palatability	Moderate to substantial improvement	Proper management will increase quality and palatability of forage.
<b>Domestic animals</b>		
Inadequate quantities and quality of feed and forage	Moderate to substantial improvement	Nutrients are managed to ensure optimal production and nutritive value of the forage used by livestock.
Stress and mortality	Slight to substantial improvement	Management results in nutritive forage improving livestock health.
<b>Air quality</b>		
Excessive greenhouse gas—carbon dioxide	Slight improvement	Management of nutrients optimizes the storage of soil carbon.
Excessive greenhouse gas—nitrous oxide	Slight improvement	Reduction in N in waste results in less N volatilization.
Excessive greenhouse gas—methane	Slight to moderate improvement	Proper nutrient management reduces methane production.
Ammonia	Slight to moderate improvement	Proper nutrient management reduces ammonia production.
Objectionable odors	Moderate to substantial improvement	Proper management and application/incorporation of manures and some biosolids reduces volatilization, volatile organic compounds, and particle transport.
<b>Water quality</b>		
Excessive nutrients and organics in groundwater	Substantial improvement	The amount and timing of nutrient application are balanced with plant needs.
Excessive salinity in groundwater	Slight improvement	Proper nutrient application should reduce salinity if nutrient source contains salts.
Harmful levels of heavy metals in groundwater	Slight to moderate improvement	The action limits the total amount of heavy metals that can be applied to a site, ensuring that harmful levels are not leached to groundwater.
Harmful levels of pathogens in groundwater	Slight improvement	The action limits the amount of manure that can be applied, thus preventing harmful levels of pathogens.
Excessive nutrients and organics in surface water	Substantial improvement	Source, amount, timing, and method of application are managed to maximize nutrient use efficiency by the crop and minimize potential for nutrient losses in leaching and runoff.
Excessive suspended sediment and turbidity in surface water	Neutral	Proper nutrient application will minimize losses due to runoff.
Excessive salinity in surface water	Slight improvement	Proper nutrient application should reduce salinity if nutrient source contains salts.
Harmful levels of heavy metals in surface water	Slight to substantial improvement	Changing pH will alter the solubility of metals. The action will reduce the application rate of heavy metals if required.
Harmful levels of pathogens in surface water	Slight improvement	Decrease application of pathogens if nutrient source contains pathogens.

TABLE 5.2. continued.

Variable	Effect	Rationale
<b>Soil condition</b>		
<b>Organic matter depletion</b>	Slight to moderate improvement	Applying sufficient nutrients will maintain or enhance biomass production.
<b>Contaminants—N, P, and K in commercial fertilizer, animal wastes and other organics</b>	Slight to moderate improvement	Proper application results in reduced risks of contamination from N, P, and K.
<b>Contaminants—salts and other chemicals</b>	Slight to moderate improvement	Decreased excess nutrients results in reduced salts and other contaminants.
<b>Compaction</b>	Slight to moderate worsening	Field operations on moist soils cause soil compaction.

are usually based on studies of crops grown with and without N fertilizer applications. Mineralization from soil organic matter depends on environmental conditions such as soil temperature and water content, so rates are expected to vary from year to year (Cabrera and Kissel, 1988).

Consequently, research is needed for pastures and haylands to develop appropriate methods to identify pools and rates of mineralizable N from soil organic matter. These data will help develop simulation models that allow estimation of mineralized N using real-time environmental conditions (Schomberg and Cabrera, 2001). Process-based models that can predict N release and uptake have been developed (Zhang et al., 2002) but have not yet been translated into decision support tools. As with release from soil organic matter, release of N from plant residues is also strongly affected by environmental conditions (Lory et al., 1995; Rodriguez-Lizana et al., 2010). Biological N<sub>2</sub> fixation by legumes can contribute significant amounts of N to grasslands.

Alfalfa–orchardgrass pastures in Iowa increased from 15 to 136 kg N ha<sup>-1</sup> yr<sup>-1</sup> as the percentage of alfalfa in the mixture increased from 11% to 55% (West and Wedin, 1985). Similarly, alfalfa–bermudagrass pastures in Texas fixed from 80 to 222 kg N ha<sup>-1</sup> yr<sup>-1</sup> (Haby et al., 2006). Despite the significant N contributions from legumes, their use has decreased in hayland and pasture systems of the USA, due in part to the difficulty of maintaining legumes in mixed stands and to the availability of low-cost N fertilizers

(Howarth et al., 2002). Recent increases in energy costs of producing N fertilizer, fertilizer prices have increased and have led to renewed interest in use of mixed stands of legumes and grasses. Therefore, research is needed to fine-tune management systems that improve the persistence of legumes in mixed stands. Also, research is needed to evaluate effects of legume proportion on N<sub>2</sub> fixation and transfer to grasses, particularly with warm-season grasses (Haby et al., 2006). Research is also needed on genetic selection of legumes for higher N<sub>2</sub> fixation capacity and tolerance to acidity and low P levels, as well as improvement of bacterial strains and inoculant carriers (Graham and Vance, 2000).

Because of the natural variability in environmental conditions, N application rates for grasslands have been typically derived from economic analyses of long-term experiments carried out with plots in which forage is cut instead of grazed (Power, 1985). Mechanical forage harvesting studies are relatively easy to conduct because they avoid dealing with uneven stubble heights and manure deposition from grazing animals. Although the results from these studies are certainly appropriate for hay and silage production, optimum N application rates for grazed grasslands need to be adjusted downward to account for recycling via deposited excreta. Research is needed to develop these guidelines.

Grazing animals return 75–95% of ingested N to the soil via feces and urine, which can become partly available for plant uptake



Proper nutrient management on pastures results in good forage yields and healthy livestock.

(Whitehead, 1995). The N available from cattle excreta for plant growth during the first year is derived mostly from inorganic N present in urine or feces, and from mineralization of some of the organic N. Excreta-derived N in subsequent years is mostly made available through mineralization of organic N. When considering excreta N that becomes plant available, it is necessary to take into account the distribution of N between feces and urine. In general, the percentage of total excreta N deposited as urine increases from 45% to 80% as concentration of diet N increases from 1.5% to 4% (Whitehead, 1995). Consequently, nutrient management should be tightly linked to diet management.

From 2% to 21% of urine N may be lost through  $\text{NH}_3$  volatilization (Mulvaney et al., 2008). In contrast,  $\text{NH}_3$  losses from cattle feces are usually low, although values as high

as 8–13% have been reported (Sugimoto and Ball, 1989; van der Molen et al., 1989). A portion of the urine and excreta that is not lost through  $\text{NH}_3$  volatilization may become plant available, depending on composition. Nitrogen in urine of cattle and sheep is mainly in the form of urea, with smaller amounts as allantoin, hippuric acid, creatinine, creatine, uric acid, and ammoniacal-N (Whitehead, 1995). With the exception of ammoniacal N, urine constituents are organic compounds that need to be mineralized before becoming plant available.

In New Zealand, a pasture of perennial ryegrass and white clover recovered 19% of the N from applications of cattle or sheep urine (Williams and Haynes, 1994). In a similar Netherlands study, perennial ryegrass recovered 16% of cattle urine N and 8% of manure N (Deenen and Middelkoop, 1992). Plant recoveries were low because of the presence of urine and manure patches with N concentrations that

greatly exceeded plant N requirements. When calculated on an area basis, these deposition rates typically range from 500 to 670 kg N ha<sup>-1</sup> for urine, and from 1200 to 2000 kg N ha<sup>-1</sup> for manure (Lantinga et al., 1987; Whitehead, 1995).

Estimations of N available through mineralization of excreted N in years following deposition may need to consider the amount of time during which the specific grassland has been under grazing management, as well as the yearly rate of accumulation and mineralization of organic N. In the Southern Piedmont region, Franzluebbers and Stuedemann (2009) evaluated the linear rate of change in soil organic N in tall fescue/bermudagrass paddocks that were either hayed or grazed (800–1700 steer days ha<sup>-1</sup> yr<sup>-1</sup>) for 12 yr, with an average inorganic fertilizer application of 246 kg N ha<sup>-1</sup> yr<sup>-1</sup>. The rate of N accumulation in the upper 30 cm was 57 kg N ha<sup>-1</sup> yr<sup>-1</sup> in hayed paddocks and 103 kg N ha<sup>-1</sup> yr<sup>-1</sup> in grazed paddocks. The extra accumulation of 46 kg N ha<sup>-1</sup> yr<sup>-1</sup> in grazed paddocks suggest that grazed grasslands likely require less fertilizer N than hayed grasslands in similar soils.

One of the greatest challenges associated with nutrient crediting from manure deposition is the lack of uniformity of nutrient distribution from deposited manure, especially in pastures with low animal densities. This issue is described in more detail later, but is a major reason why there is a general lack of U.S. research data on N (and other nutrients) requirements of grazed pastures. Consequently, research is needed to characterize the nutrient distribution from deposited manure in grazed grasslands, especially with different grazing methods, to fine-tune fertilizer N recommendations.

When natural sources of N are not sufficient for optimum grassland performance, N sources such as commercial fertilizers, animal manures, and biosolids can be used. Livestock manures and biosolids are generally lower cost per unit of nutrient than commercial fertilizers and they are readily available for most producers.

Livestock and poultry in the USA excrete 1.6 billion tonnes of fresh manure annually

(Table 5.3), and this excreted manure contains approximately 75% of the commercial fertilizer N consumed in the USA each year. In addition, there are 40% fewer livestock and poultry farms than 30 yr ago, but the number of animals has increased (U.S. Department of Agriculture–National Agricultural Statistics Service [USDA-NASS], 2009). Although most of the manure produced by cattle in the USA is excreted directly and nonuniformly, onto pasture and rangelands, the great majority of the manure generated by pigs and poultry is collected and can be managed as a crop nutrient resource.

Manures that are collected and managed are important nutrient sources for pastures and haylands, especially in the lower midwest and southern and eastern USA. Total N excreted in the collectable fraction of livestock and poultry manure is nearly 28% of U.S. commercial fertilizer N consumption, but 30–85% of this N may be lost to the atmosphere during manure storage and application depending on the manure management system. Therefore, the potential N replacement value of collectable manure is likely less than 15% of U.S. commercial fertilizer N consumption.

Biosolids are another potential source of nutrients for pastures and haylands. Approximately 57 million dry tonnes of biosolids are generated annually from the treatment of over 45 trillion liters of wastewater (USEPA, 1999). Roughly 40% of these biosolids are beneficially reused via land application. Biosolid applications to pastures are also highly regulated. The USEPA requires a 30-d interval between application of biosolid and hay harvest or grazing to minimize the potential for direct ingestion of the biosolids and any pathogens present in the material (USEPA, 1994).

A significant challenge facing producers is that the nutrient composition of manures and biosolids generally is not balanced relative to crop nutrient requirements. Applying these materials at rates needed to meet plant N needs creates overenrichment of soil P. Although substantial variations in manure nutrient composition exist, manure N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O is typically around 1:1:1 (Council for Agricultural Science and Technology [CAST], 2006),



...nutrient composition of manures and biosolids generally is not balanced relative to crop nutrient requirements”

**TABLE 5.3.** Estimated quantities of manure and manure nutrients produced annually in the USA compared to consumption of commercial N, P (as  $P_2O_5$ ), and K (as  $K_2O$ ) fertilizer.

	Animals <sup>1</sup>	Manure <sup>2</sup>	N <sup>2</sup>	P <sub>2</sub> O <sub>5</sub> <sup>2</sup>	K <sub>2</sub> O <sup>2</sup>
	Millions	Millions of tonnes	Thousands of tonnes		
Beef cattle	60	1191	5199	2424	4299
Milk cattle	17	257	1597	617	839
Horses	4	37	133	44	48
Hogs	68	74	596	256	338
Layers	350	11	203	146	90
Pullets	106	1	17	12	8
Broilers	1603	44	485	324	330
Turkeys	107	8	119	80	66
Ducks	4	< 1	2	1	1
All animals	2319	1623	8,351	3904	6019
Collectable manure <sup>3</sup>		424	3098	1471	2037
Deposited manure <sup>4</sup>		1,199	5253	2433	3982
Fertilizer consumption <sup>5</sup>			11,117	3940	4365

<sup>1</sup>Number of animals in inventory from 2007 Census of Agriculture (U.S. Department of Agriculture–Natural Agricultural Statistics Service [USDA-NASS], 2009). <sup>2</sup>Excretion values from USDA–Natural Resources Conservation Service (USDA-NRCS) Agricultural Waste Management Field Handbook (USDA-NRCS, 2008). <sup>3</sup>Includes 100% of manure from beef finishing cattle, 15% of manure from other beef cattle (not including beef cows), 50% of manure from lactating dairy cows, 15% of manure from other dairy cattle, and 100% of manure from hogs and poultry. <sup>4</sup>Includes 100% of manure from beef cows, 85% of manure from other beef cattle (not including beef finishing cattle), 50% of manure from lactating dairy cows, 85% of manure from other dairy cattle, and 100% of manure from horses. <sup>5</sup>Average 2000–2009 U.S. commercial fertilizer consumption (American Plant Food Control Officials and The Fertilizer Institute [AAPFCO-TFI], 2011).

whereas removal rates from grazed pastures are closer to 3:1:3 (Joern et al., 2009). When animal manures, biosolids and most other nutrient rich by-products are applied at N-based rates to pastures, P applications are usually 2–4 times greater than crop-P removal. Repeated applications of these materials to pasture and hayland result in soil-test-P levels that are greater than those needed for optimum forage yields. High soil-test-P levels result in elevated soluble-P concentrations in water runoff from pastures. The effect of elevated soil-test-P levels and nutrient runoff from manured pastures and haylands on surface-water impairment are discussed in later sections.

Manure also lacks consistency in both nutrient content and particle size. Despite attempts to standardize procedures for both manure sampling and analysis (Peters, 2003), a review of numerous state Extension bulletins found on the Web clearly showed there is neither a single, widely accepted strategy for obtaining

a representative manure sample for analysis nor uniform procedures for analyzing manure nutrient content.

Manure spread on pastures and haylands in the USA is usually surface applied with rear- and side-discharge spreaders, application uniformity with solid dairy and beef cattle manure had a coefficient of variation greater than 100% (Norman-Ham et al., 2008). Poultry litter is a more consistent material and more uniform rates can be achieved with proper overlap of each spreader pass. Achieving application uniformity with liquid-manure applications is a challenge for liquid tank spreaders and numerous irrigation systems.

One of the most significant challenges to achieve optimum utilization of manure and other organic by-products on pastures and haylands is the wide range of algorithms states use to determine manure nutrient availability. Among 34 states, 27 different variables were

used to determine plant-available manure N and individual states use from 5 to 12 variables (Joern et al., 2009; Table 5.4). Although the number of variables required is indeed large, once the manure source is determined, 12 states use only one factor (e.g., total manure N) and 15 states use only two factors (e.g., total manure N and application method). Although all states require manure total N as part of their manure-N-availability algorithm, 14 states do not require the ammonium ( $\text{NH}_4$ ) form of N, which is the manure-N component most likely to volatilize when surface applied to pastures and haylands. In addition, roughly one-third of the states in the database do not account for mineralization of residual N in the years following application. And, for the states that estimate residual manure-N credits, the time frame varies from 1 to 5 yr after application.

All but one state includes method of application to determine plant-available manure N. However, only 13 of 34 states use time (months) between manure application and crop N uptake to determine manure-N availability. It is likely that manure applications made to dormant pastures have significantly greater potential for N loss prior to crop uptake than manure applied to actively growing plants, yet the majority of states surveyed do not

include this variable. This lack of a timing variable in many state algorithms is particularly problematic for producers with liquid manure, as storage limitations often require applications to crops that are not actively growing. These large discrepancies in algorithms can result in more than 50% differences among states for estimates of plant-available N from manure, and is probably the single greatest factor affecting optimum utilization of manure N in agricultural fields.

Studies to develop N recommendations for grasslands are usually carried out with commercial fertilizers such as ammonium nitrate that do not undergo significant  $\text{NH}_3$  losses in neutral or acidic soils (Knight et al., 2007). Losses through  $\text{NH}_3$  volatilization should be taken into account when using sources that lead to such losses, such as animal manures and commercial fertilizers that contain urea, as well as ammoniacal fertilizers applied to soils with  $\text{pH} > 7.5$ . For example,  $\text{NH}_3$  losses ranged from 6% to 14% of the available N when poultry litter was surface applied to tall fescue at 70 kg available N  $\text{ha}^{-1}$  in Alabama, Georgia, and Tennessee (Marshall et al., 1999). Similarly,  $\text{NH}_3$  losses ranged from 12% to 46% of the applied N when urea was surface applied to tall fescue at 50 kg N  $\text{ha}^{-1}$  in Georgia (Vaio et al., 2008). In

“discrepancies in algorithms can result in more than 50% differences among states for estimates of plant-available N from manure”



Soil sampling and testing is imperative for good forage production and environmental protection.



methods that reduce both  $\text{NH}_3$  loss and surface runoff are desirable for agronomic and environmental reasons.”

**TABLE 5.4.** Data needed to determine availability of manure N following manure application in 34 U.S. states.<sup>1</sup>

Input data	AL	AR	CA	CO	DE	FL	GA	IA	IL	IN	KY	KS
Number of years credited	1	1	3	3	4	1	1	3	4	1	2	3
Manure total N	R	R	R	R	R	R	R	R	R	R	R	R
Manure $\text{NH}_4\text{-N}$	R			R	R				R	R		R
Manure dry matter (%)												
Animal type		R	R	R	R	R		R	R			
Manure is from poultry		R	R	R	R	R	R	R	R	R	R	
Manure contains bedding									R			
Storage type		R	R			R	R					R
Manure is liquid				R			R	R	R	R	R	R
Equipment type			R									R
Manure is injected	R	R	R		R	R	R	R	R	R	R	R
Manure is irrigated	R	R	R			R	R	R	R	R		R
Manure is aerially applied												
Days to incorporation	R	R	R		R	R	R	R	R	R	R	R
Application month	R	R								R	R	
Region of state	R									R		
Field is irrigated with water												
Field is artificially drained		R	R									
Field is annually manured			R								R	
Soil organic matter (%)		○										
Soil surface texture												
Soil drainage class		○	R									
Application rate												
Crop canopy/cover/type										R	R	
Application made in year of crop utilization										R	R	
Long-term monthly air temperature												
Average days in month soil is saturated												

<sup>1</sup>R indicates required input value and ○ indicates optional input value.

the same study,  $\text{NH}_3$  losses from a solution of urea–ammonium nitrate applied at 50 kg N ha<sup>-1</sup> ranged from 6% to 33%. Additional information on  $\text{NH}_3$  losses from grasslands is presented in the air-quality section.

Broadcast applications of manures and N fertilizers are common in grasslands, and may lead to significant  $\text{NH}_3$  losses, and exposure to surface runoff increases potential contamination of surface waters (Pierson et al., 2001). Consequently, methods that reduce both  $\text{NH}_3$  loss and surface runoff are desirable for agronomic and environmental reasons. For example, surface or subsurface banding of N fertilizers may help reduce  $\text{NH}_3$  loss and improve N-use efficiency (Raczowski and

Kissel, 1989; Vigil et al., 1993). A recently developed subsurface applicator that applies poultry litter in a band 5 cm deep and 4 cm wide (Pote et al., 2003; Warren et al., 2008) may be useful in reducing the surface area of poultry litter subject to  $\text{NH}_3$  volatilization and N contamination of surface runoff. These applicator systems are encouraging, but are in the early stages of development.

### Phosphorus

Phosphorus requirements of grasslands depend on soil-P availability and forage uptake capacity. Phosphorus uptake by forages can vary from 9 kg P ha<sup>-1</sup> for white clover (Brink et al., 2001) to 83 kg P ha<sup>-1</sup> for johnsongrass (Pierzynski and Logan, 1993), with

	MA	MD	MI	MN	MO	MS	MT	ND	NE	NJ	NM	OH	OK	OR	PA	RI	SD	TN	UT	VT	WA	WI
	6	4	4	3	3	1	3	3	4	6	3	1	3	1	6	6	2	4	1	3	1	3
	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	R	R	R		R	R			R	R	R	R			R	R	R	R		R		
										R					R					R		
		R	R	R			R	R	R	R	R			R	R			R	R			R
	R	R	R	R	R		R	R	R	R	R		R	R	R		R	R	R	R		R
			R		R							R										
		R					R		R	R	R	R			R			R	R	R		
			R		R				R	R	R	R		R	R			R		R		
				R	R		R	R				R						R				
	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
					R	R		R		R			R				R	R	R		R	
											R	R										
	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
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bermudagrass taking up intermediate amounts of 29 to 73 kg P ha<sup>-1</sup> (Brink et al., 2004; Read et al., 2006). Most available P in soils originates from mineralization of soil organic matter and plant residues plus P desorbed from clay minerals and amorphous iron and aluminum oxides. Soil-P availability varies with soil type and is commonly evaluated with soil tests such as Bray1, Mehlich-1 and Mehlich-3 (Mehlich, 1953). A small amount of P (0.2 to 1.5 kg P ha<sup>-1</sup>) is also received yearly with precipitation (Newman, 1995; Owens et al., 2003).

Because of the many factors involved in P availability and P uptake, recommendation rates for P fertilizer to optimize forage production are usually determined empirically

by conducting studies for selected forage, soil, and environmental conditions. Two strategies for fertilizing grasslands with P are considered; one emphasizes fertilizing the forage, whereas the other emphasizes fertilizing the soil.

Both strategies require determination of the optimum soil-test level for a given soil type and forage. The optimum level is the soil-test level above which forage yield or quality does not respond to added P, and is commonly determined by carrying out studies with two treatments (control without added P, or a high P rate) in soils with different soil-test levels, ranging from low to high. For example, in Florida soils bahiagrass did not respond to added P when Mehlich-1 test levels were above 16 mg P kg<sup>-1</sup> (Stanley and Rhoads, 2000).



In contrast to most commercial fertilizers, ...animal manures and biosolids have variable amounts of plant-available P.”

The strategy that emphasizes fertilizing the forage is based on applying the amount of P fertilizer needed to obtain optimum forage yield at the current soil-test P-level, implying P should be applied when the soil-test P is below the optimum level. To determine the amount of P fertilizer to be added, P-rate studies are conducted at different soil-test-P levels below the optimum level. The other strategy, which emphasizes fertilizing the soil, is based on adding the necessary P fertilizer to bring the soil to, or maintain it at, the optimum soil-test-P level. Field or laboratory studies are usually needed to determine how much P is necessary to add to soils with lower soil tests to bring them up to the optimum level. For example, in Georgia Piedmont soils, it took 4.1 mg P kg<sup>-1</sup> to increase Mehlich-1 P level by 1 mg P kg<sup>-1</sup> (Pierson et al., 2001); in Alabama it took an average of 4.5 mg P kg<sup>-1</sup> per soil-test unit (Cope, 1983). Once the optimum soil-test level is achieved through addition of P fertilizer, this fertilization strategy consists of adding an amount of fertilizer P annually that is equal to that removed from the grassland to maintain the soil test at the optimum level.

Many studies have been conducted to establish P requirements of agronomic crops, but fewer have evaluated P requirements of forage crops and pastures (Pant et al., 2004). Part of the reason is that many grasslands are fertilized with animal manures, which have ratios of available N to available P that are much lower than those required by most forages. Further, as for N, most studies to evaluate P response of forages have been conducted with plots that are cut instead of grazed, which raises the question of their relevance for grazed situations. In general, cattle excrete about 75–90% of P in the diet, with most excreted P found in feces rather than in urine. However, P in excreta is utilized slowly because inorganic P in feces has low solubility and the organic P mineralizes slowly (Whitehead, 2000).

Few U.S. studies have compared P responses under hayed and grazed systems. Forage productivity and P uptake of smooth brome grass in Iowa were greater in hayed and grazed plots than in nongrazed plots (Haan et al., 2007). In New Zealand, dry-matter production was greater in grazed than in mowed trials (Morton and Roberts, 2001), and

in Australia, more frequent mowing resulted in greater response to P than did less frequent mowing (Cayley and Hannah, 1995). These results suggest forage production and P uptake are stimulated by forage harvest, either by grazing or hay harvest. Additional research should be conducted in the USA to confirm these results.

Phosphorus sources for grasslands include commercial fertilizers as well as animal manures and biosolids. The total P excreted in livestock and poultry manure in the USA is nearly identical to the commercial-P fertilizer consumption; but the P that can realistically be collected and managed as a nutrient resource is only about 37% of commercial fertilizer-P consumption (Table 5.3). In contrast to most commercial fertilizers, of which > 90% of the P is in plant-available form (water-soluble P + citrate-soluble P), animal manures and biosolids have variable amounts of plant-available P.

O'Connor et al. (2004) determined total P and percent phytoavailability of 12 biosolids to bahiagrass grown in two soils in the greenhouse compared to triple superphosphate (TSP, 100% phytoavailability). One biosolid had a total-P content of 3.2 g P kg<sup>-1</sup>, whereas the remaining 11 had total-P contents ranging from 21.5 to 39.0 g P kg<sup>-1</sup>. The relative bioavailability of two biosolids (which were produced through biological P removal processes without addition of Al) was high, ranging from 74% to 130% in the two soils used. In contrast, a biosolid produced with the above process, but with the addition of Al, had relative phytoavailability ranging from 31% to 63%. On average, pelletizing two of the biosolids reduced their phytoavailability (compared with nonpelletized form) from 80% to 55% and from 40% to 11%. Oladeji et al. (2008) determined P phytoavailability of two biosolids and poultry manure with respect to TSP in a greenhouse study using bahiagrass for 6 mo, followed by ryegrass for 5 mo, and a second bahiagrass for 4 mo. A field study was also carried out with improved pastures for 2 yr. Average P phytoavailability for the combined studies was 49% for poultry manure, 56% for a conventionally processed biosolid, and 84% for a biosolid that underwent a process similar to biological P removal. These results show that bioavailability of biosolid P depends on the



“Should total manure P or available manure-P values be entered into the P index or other risk assessment tool algorithms?”

Accurately calibrated fertilizer spreaders ensure good forage yields without excessive loss of nutrients to the environment.

wastewater treatment used and on subsequent treatments such as composting and pelletizing.

Several U.S. studies have evaluated P uptake in grasses fertilized with animal manures (e.g., Brink et al., 2004; Sistani et al., 2004), but few have compared the phytoavailability of manure P with respect to commercial P fertilizers.

There is variability among states in the proportion of manure P assumed to be plant available. In a survey by Joern et al. (2009), all but 8 of the 34 states surveyed assume that manure total P is 100% plant available relative to commercial fertilizer. Manure-P availability relative to commercial fertilizer P for the other eight states ranges from 60% to 90% and four of these states estimate residual-P availability in subsequent years. States that use less than 100% fertilizer-P equivalent for manure generally allow greater rates when manure is applied based on crop-P removal. Subsequent soil testing can confirm the need for additional P applications, but when manure is applied based on crop-P removal, the soil-test P can rise above agronomically responsive levels. This raises the question for those states that credit manure at less than 100% commercial fertilizer P efficiencies. Should total manure P or available manure-P values be entered into the P index or other risk assessment tool algorithms?

Because P recommendations are usually based on commercial fertilizers with high phytoavailability (> 90%), additional research should be carried out to characterize the P phytoavailability of different animal manures and biosolids with respect to commercial fertilizers such as TSP. Furthermore, depletion of rock phosphate deposits in the not-so-distant future will make it necessary to develop processes to recover as much P as possible from animal manures and biosolids to maintain agricultural productivity (Cordell et al., 2009). There is potential to develop recycled P materials with concentrations similar to those of commercial fertilizers (Szogi et al., 2008; Szogi and Vanotti, 2009), but the phytoavailability of these recycled products needs to be known to optimize application rates (Bauer et al., 2007).

With regard to placement, P fertilizers are usually broadcast onto pastures and haylands and as a result, surface runoff may solubilize some of the fertilizer P and transport it to surface waters (Franklin et al., 2005). Therefore, subsurface banding would be a preferred method for grasslands where surface runoff has the potential to contaminate surface waters with P (Pote et al., 2003).

### Potassium

Potassium (K) fertilizer requirements for grasslands are determined from plant-available

K and K uptake by the forage. Forage K uptake can be high, especially when forage is cut for hay or silage. Alfaro et al. (2003) found that plant uptake was 140 kg K ha<sup>-1</sup> when grazed and 415 kg K ha<sup>-1</sup> when cut for silage. Because of high removal rates, most grassland requires K fertilizers to obtain and maintain optimum levels of dry-matter production.

Plant-available K in pastures is derived from soil minerals, senesced plant materials, animal excreta, and precipitation. The supply derived from soil minerals varies with soil type and environmental conditions (Havlin et al., 2005), whereas the amount of K recycled from senesced materials can vary with plant species and dry matter production. Uptake by tall fescue in Georgia was 64 kg K ha<sup>-1</sup> yr<sup>-1</sup> in the top growth and 34 kg ha<sup>-1</sup> in the roots (Wilkinson and Lowrey, 1973). Significant

amounts of K can be returned in animal excreta. Whitehead (2000) estimated 105 kg K ha<sup>-1</sup> are returned in urine and 23 kg K ha<sup>-1</sup> are returned in feces when dairy cattle graze at a density of 700 cow-days ha<sup>-1</sup> yr<sup>-1</sup>. In New Zealand, excretal returns of K ranged from 180 to 500 kg K ha<sup>-1</sup> (Early et al., 1998). In contrast, K received in precipitation is relatively low, ranging from 2 to 20 kg K ha<sup>-1</sup> (Whitehead, 2000). For example, rates were 5.1 to 6.3 kg K ha<sup>-1</sup> yr<sup>-1</sup> in Ohio (Owens et al., 2003) and 6.4 to 9.5 kg K ha<sup>-1</sup> yr<sup>-1</sup> in southwest England (Alfaro et al., 2003).

As with P, K fertilization of grasslands can be based on two main strategies: fertilizing the forage or fertilizing the soil. Most university recommendations use the strategy of fertilizing the forage, which is based on results of K response studies under various soil-K

Vegetated riparian areas remove nutrients before they can enter waterways.



levels. These studies are conducted under optimum N fertilization because the response to K depends in part on N availability (Kayser and Isselstein, 2005). In K-response studies forage is cut and removed instead of being grazed, usually ignoring recycling of K through senesced plants and animal excreta (mainly urine). As a result, fertilizer recommendations based on soil-K levels are likely too high for pastures under intensive livestock production (Kayser and Isselstein, 2005). Therefore, additional research is warranted to develop methods to account for K recycling for grazed grasslands. Accounting for K recycling may allow development of K balances (input–output) that are close to zero, thereby reducing K leaching losses. In addition, avoiding large, positive K balances is important to reduce Ca and Mg leaching, thereby reducing the occurrence of hypocalcemia and hypomagnesemia in grazing cattle (Early et al., 1998; Owens et al., 2003).

Potassium amendments for grasslands include commercial fertilizers as well as animal manures and biosolids. Livestock and poultry in the USA excrete 38% more K annually than commercial fertilizer K consumed. Further, the fraction of manure K collected for application is nearly 47% of commercial fertilizer K consumed (Table 5.3). Potassium availability in animal manures is usually assumed to be near 100% because K is present in the inorganic form (Eghball et al., 2002). Availability of K in composted livestock manure and biosolids has also been found to be near 100% (Wen et al., 1997). However, K utilization in a Wisconsin field study was only 73% for injected dairy slurry (Motavalli et al., 1989). Clearly, additional research on K availability in by-products is needed. In terms of placement method, K fertilizers are usually broadcast on pastures because the high solubility of K ensures relatively fast movement into upper soil layers (Sistani et al., 2003; Warren et al., 2008).

### Code 590–Criteria Assessment

*Can a nutrient budget be developed for N, P, and K based on all potential sources of nutrients including animal manures and organic by-products, wastewater, commercial fertilizer, crop residues, legume credits, and irrigation water?* Development of a nutrient budget taking into account all

sources of nutrients requires information on the nutrient availability of the different sources. As described above, there is sufficient information on N release from most sources, but there is considerable variability among state laboratory recommendations, especially for N availability in animal manures. Also, average values commonly used for N release from organic sources have been developed from data sets with large variability because of variations in mineralizable N and environmental conditions. Thus, research is needed to develop tools for fast determination of pools and rates of mineralizable N in organic sources, as well as models to estimate N mineralized with the use of real-time environmental data. Although such models have been developed (Zhang et al., 2002) there is a need to translate them into decision-support tools to guide nutrient application.

With regard to P and K budgets, there is information on the average availability from many sources, but additional research is needed to determine phytoavailability of P and K in organic sources such as biosolids, manures, and other organic fertilizers. In summary, nutrient budgets can be developed with the use of average availability values (VanDyke et al., 1999; Shepard, 2005), but additional work is needed to fine-tune N, P, and K availability based on rates of nutrient release. In addition, there is a need to develop on-farm nutrient budgets that quantify multiple pathways of nutrient input and loss over time under different management systems (Vitousek et al., 2009). These needs may be usefully served by developing more comprehensive models.

Another significant challenge in developing nutrient budgets is that, in most states, fertilizer recommendations for pastures are the same or nearly the same as they are for hay fields, even though about 75–90% of the nutrients consumed by grazing animals are returned in the manure (Whitehead, 2000). The lack of differences in fertilizer recommendations between pastures and hay fields is most likely because manure deposited by pastured animals is not uniformly distributed across the field in extensively grazed pasture systems. Numerous studies have shown that manure deposition is concentrated around shade trees, watering sources, and supplemental feed bunks



fertilizer  
recommendations  
based on soil-K  
levels are likely  
too high for  
pastures under  
intensive livestock  
production”



Nutrient planning should use soil, tissue, and manure samples that are collected, processed, and analyzed...”

(Mathews et al., 1994; White et al., 2001; Dubeux et al., 2009). Therefore, most state fertilizer recommendations assume that lack of uniformity in deposition makes it nearly impossible to credit these nutrients properly to reduce fertilizer recommendations for extensive pastures.

However, a growing number of producers have adopted managed grazing methods where animals have access to limited land areas for short time periods (a few hours to a few days). In these grazing methods, manure deposition is more uniform than in traditional, extensive pasture management. Lory and Kallenbach (1999) estimated it might take more than 25 yr to have at least one manure pile per square meter of a pasture under traditional continuous grazing; with a 2-d grazing period this time would be reduced to less than 2 yr. With 1-d grazing periods, manure should be relatively uniformly distributed throughout the grazing paddock and nutrient credit in the form of reduced fertilizer recommendations should be developed. Currently, very few states have developed fertilizer recommendations for intensively managed grazing systems and it needs more research. It is also important to recognize that different forms of grazing management can affect the rate of forage growth, hence altering plant uptake of applied nutrients and affecting the risk that unused nutrients will be lost to the environment.

*Can realistic yield goals be established based on soil productivity information, historical yield data, climatic conditions, level of management and/or local research on similar soil, cropping systems, and soil and manure/organic by-products tests?* In several states, fertilizer recommendations for grasslands are based on nutrient addition response studies instead of yield goals. However, those states that use yield goals usually provide guidelines for setting realistic yield goals in extension bulletins or fact sheets. These guidelines range from using the average yield from the last 3–5 yr plus an increase of 5–20%, to a 5-yr average plus one standard deviation, or to 80–90% of an estimated attainable yield based on a simulation model and weather data from several years (Fixen, 2006). The need for long-term yield data for either N response

curves or forage yields is based mainly on weather variability across years. Because of this variability and current limitations in long-term weather prediction, a promising approach that needs additional research is the adjustment of yield goals or N rates within the growing season by using real-time tools like sensors and weather-driven models.

*Do nutrient management plans need to specify the source, amount, timing, and method of application for each field to achieve production goals while minimizing movement of nutrients and other potential contaminants to surface and/or ground water?* The available literature indicates that nutrient management plans that take into account the source, timing, method of application, and level of management for each field (or within a management zone) lead to lower N and P application rates and lower N and P losses (VanDyke et al., 1999; Beegle et al., 2000; Delgado et al., 2005; Shepard, 2005).

*Can nutrient planning be based on current soil- and tissue-test analyses that are collected and processed with the use of land-grant approved practices and by labs meeting performance standards?* Nutrient planning should use soil, tissue, and manure samples that are collected, processed, and analyzed with the use of practices approved by land-grant universities (Peters, 2003).

*Are all soil-test analyses less than 5 yr old useful for nutrient planning?* For fields that have been receiving recommended rates of nutrient applications, 5-yr-old soil tests may be adequate for nutrient planning. However, in fields that have been receiving high rates of manure or biosolid applications, soil-test P may be increasing rapidly (Pierson et al., 2001) and as a result, 5-yr-old soil tests may not be adequate for nutrient planning. In those situations, more recent soil tests may be needed. Additional research is needed to determine the short-term increase in soil-test values under those conditions.

*Is it possible to predetermine analyses pertinent to monitoring and amending the annual nutrient budget?* The use of sensors and inorganic N analysis during the growing season may allow adjustment of the N budget

based on forage and soil conditions (Flowers et al., 2004; Meisinger et al., 2008), but additional research would be needed to adapt these tools to use in grasslands.

*Is it important or critical to adjust soil pH to an adequate level for (effective) nutrient availability and utilization?* Because the availability of some nutrients increases with pH while the availability of other nutrients decreases with pH, a pH range of 6–6.5 is usually where most nutrients are adequately available (Havlin et al., 2005). In addition, forages have different acidity tolerance. Therefore, soil pH should be adjusted, taking into account crop tolerance to acidity and nutrient availability.

*Are nutrient application rates based on land-grant university recommendations using soil tests, yield goals, and management capabilities adequate for nutrient planning?* Land-grant university recommendations are typically based on many years of research and as such provide an excellent approach to develop adequate nutrient management plans that lead to reduced nutrient losses (Lawlor et al., 2008). However, data collected from row crops suggest that in many cases these recommendations lead to overapplication of nutrients indicating there is the potential to reduce nutrient applications by up to 20% without compromising yields. Further, manures are commonly applied to pastures naturally or from storage areas. These manures vary in distribution on the pasture, quantity per year, nutrient concentrations, and nutrient availability, making planning more difficult.

*Should N applications using commercial fertilizers match recommended rates for pastures/haylands as closely as possible?* Application of commercial N fertilizers should match recommended rates as closely as possible to minimize nutrient losses (VanDyke et al., 1999; Delgado et al., 2005).

*Is conservation management unit (CMU) risk assessment (using the appropriate tool) needed for manure and organic by-products to adjust the amount, placement, and timing of the nutrient application?* When manure, organic by-products, or

biosolids are applied, it is important to carry out a risk assessment with a tool such as the P index to adjust nutrient management so as to minimize the environmental impact of the added nutrients (Butler et al., 2010).

*Are sampling and analytical methods for manures adequate for use in nutrient budgeting?* Most methods for manure analysis determine the total amounts of nutrients in the manure, not the plant-available amounts (Peters, 2003). Consequently, in current methods for nutrient budgeting, a certain proportion of the total amount of each nutrient is assumed to be plant available. As discussed above, these proportions are interpreted differently among states, especially for N and P. Although some research has been conducted to develop methods for assessing amounts of available nutrients in manures, none is currently in use.

Research should continue to develop methods that can measure plant-available N and P in manures, organic by-products, and biosolids. Furthermore, methods that measure pools of mineralizable N and P could be coupled to simulation models to estimate rates of release using real-time environmental conditions during the growing season. Process-based models capable of such simulations are under development (Zhang et al., 2002; Giltrap et al., 2010).

*Is a cumulative record of manure analyses (3 yr?) adequate for use as a basis for nutrient allocation to pastures and hay fields? Are “book values” on composition acceptable?* Animal operations that use consistent forage/rations should achieve consistent manure composition in a relatively short time. Under these conditions, a 3-yr cumulative record of manure analyses should be sufficient to demonstrate consistent manure composition (Moore et al., 1995b).

*Do manure analyses need to include nutrient and specific ion concentrations, percent moisture, percent organic matter, and salt concentration?* An accurate method to determine mineralizable N in manures is not available, so current manure analyses for N include inorganic N (mainly ammoniacal N) as well as total N (Peters, 2003). For P and K,

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manures vary in distribution on the pasture, quantity per year, nutrient concentrations, and nutrient availability, making planning more difficult.”



Nutrient management becomes more complicated when manure sources are used due to uncertainties in nutrient concentration and release rate.

total amounts are usually sufficient to estimate availability, although some research shows considerable variability in use efficiency of P and K (Motavalli et al., 1989; Wen et al., 1997; O'Connor et al., 2004). Determination of salt concentration or osmotic potential would be useful for manures that are to be applied close to the seed or young plants. Percent moisture (or percent solids) in manures and biosolids is essential for determining organic residue additions used when calculating soil erosion in RUSLE2. Otherwise this information would be needed only when nutrients are reported on a dry-matter basis.

*Is it critical that the application rate of liquid materials shall not exceed the intake or infiltration rate, minimize ponding, and avoid runoff?* Liquid manures applied at rates that exceed the soil infiltration rate can lead to ponding and runoff, as well as preferential flow to subsurface drain tiles, resulting in potential contamination of surface waters. In a literature review, Hoorman et al. (2010) suggested that liquid manure application rates should not exceed the remaining available water holding capacity of the surface 20 cm of soil at the time of application and suggested that application rates should be limited to 120,000 L ha<sup>-1</sup> for surface-drained cropland, regardless of the remaining available water-holding capacity of the soil. Because many hayfields and pastures are on sloping land, the rates of intake and runoff may vary with ground cover at the time

of application. These relationships need to be understood so better estimates of application rates can be made. Fields subject to cracking or root channeling are potentially more problematic, so great care must be taken when applying liquid materials in these situations.

#### *Are N application rate guidelines for manure and organic materials sufficient?*

Nitrogen-availability algorithms have been developed to determine application rates for manures and other organic materials, including biosolids and composted materials, in most states.

Availabilities of biosolid N are generally consistent among states and are mandated via state or federal regulations. However, N-availability algorithms used are not necessarily supported by research. Nitrogen-availability algorithms for manures vary greatly from state to state and are probably the greatest single factor affecting optimum N utilization of these materials. In addition, most states do not include time of application relative to crop uptake for any organic materials. More research in this area is needed, especially in-season modeling based on actual weather data, to improve the ability to predict actual crop-N needs from year to year.

#### *Are P application rate guidelines for manure and organic materials sufficient?*

Phosphorus-availability algorithms for manures and other organic materials are more consistent among states than are those for N. Phosphorus availability in biosolids can be greatly affected by the process used to concentrate solids (i.e., polymers, Fe, Al or Ca flocculating agents, biological recovery), yet these variables are not generally considered. Most states consider manure P to be 100% available relative to commercial fertilizer P, though this is not uniformly true. However, because manures are often applied on an N-rate basis, P deficiencies resulting from manure and other organic materials are rare. In addition, regular soil testing will help determine the impact of these P sources on plant available P. However, more research to determine P availability from manures and biosolids is needed to improve predictions for availability of P in manures, biosolids and other organic P sources relative to commercial P sources.

***Are K and other nutrient application rate guidelines sufficient?*** Nearly all states assume that K availability from organic sources is 100% available relative to commercial fertilizer K, and this assumption is generally supported by research, though the availability of research data in this area is limited. Excessive K applications to grass pastures in the early spring under high soil moisture conditions can result in high levels of nitrate-N and lowered magnesium levels in the forage, which can lead to animal health problems like nitrate poisoning, hypomagnesemia and hypocalcemia in cattle. Although this is generally not a problem with biosolids, because of their low K content, the judicious use of high-K manures on pastures should be stressed.

***Should timing and method of nutrient application (especially N) correspond with plant nutrient uptake characteristics considering relevant risk variables, including strategies to minimize nutrient losses?*** Ideally the timing of nutrient applications should correspond with plant nutrient uptake, especially for N, which is easily accomplished in the cases of commercial fertilizers and poultry litter. However, with liquid manure systems many producers do not have adequate storage to apply these manures with proper timing relative to crop N needs. Most nutrients are applied to the surface of grassland soils, making them subject to runoff losses, though some advances in subsurface application equipment for pastures have been made. Shallow injection would help reduce ammonia volatilization and P runoff potential, but surface applications are far more prevalent, because of equipment availability and the potential damage to plants from injected applications. There is also some risk that subsurface application increases loss of N by leaching.

### Summary

The scientific literature supports the principle that judicious nutrient management can improve utilization of manure and other organic by-products while reducing environmental contamination. However, significant advances must be made before the use of these materials can be optimized. For example, although all states provide

guidelines and recommendations for how to utilize manures on pastures and haylands best, the recommendations and algorithms lack consistency among states, even those within a similar geographic region. The greatest differences are those related to how the availability of manure N is calculated. These differences generally overshadow those in fertilizer recommendations among states within similar geographic regions, and are due at least in part to the lack of rapid methods to measure pool sizes and release rates of mineralizable N.

Biosolids availability algorithms are quite consistent across all states, but the algorithms are not necessarily supported by the scientific literature. Few states have developed fertilizer recommendations that are suitable for intensively managed grazing operations. Few significant advances have been made in equipment for surface application of manure, so uniformity of distribution remains a significant challenge. Overall, there is a need to develop on-farm nutrient budgets that quantify multiple pathways of nutrient input and loss over time under different management systems. This may require expanded efforts in modeling.

## MINIMIZE AGRICULTURAL NONPOINT SOURCE POLLUTION OF SURFACE AND GROUNDWATER RESOURCES

### Surface Runoff

In many areas of the USA, nutrient runoff from pastureland can lead to water-quality problems including eutrophication of lakes and rivers, one of the most widespread water-quality impairments of U.S. waterways (USEPA, 1996). Several studies show nutrient concentrations in runoff increase with intensity of agricultural land use (e.g., Dillon and Kirchner, 1975; Owens et al., 1996; Pionke et al., 1996; Carpenter et al., 1998). Excessive manure applications were the greatest potential threat leading to eutrophication (Duda and Finan, 1983). Usually P is the limiting element for eutrophication in freshwater systems, whereas N usually limits in brackish and salt water (Schindler, 1977).

Phosphorus in runoff water can be dissolved (soluble) or particulate. Particulate P includes

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there is a need to develop on-farm nutrient budgets that quantify multiple pathways of nutrient input and loss over time under different management systems.”



...best management practices for reducing P loss should focus on those that are aimed at reducing losses in surface runoff, whereas those for N should focus on reducing losses as leaching.”

all solid-phase forms, such as P associated with soil particles and organic matter. Because most pastures and haylands have very low rates of water erosion, the majority of P in runoff is the soluble form (Sharpley et al., 1992; Edwards et al., 1993; Shreve et al., 1995). Water-soluble P is the form most readily available for algal uptake (Sonzogni et al., 1982). Concentrations of P and N in runoff water from pastures can be very high following manure or fertilizer applications (Edwards and Daniel, 1992a, 1992b).

Although P-induced eutrophication is generally considered a freshwater phenomenon (Correll, 1998), there is strong evidence that P has a greater influence than N on hypoxia in the northern Gulf of Mexico (Lohrenz et al., 1999a, 1999b; Sylvan et al., 2006). In the Mississippi River plume, bioassays indicated P was limiting during periods of highest river flows (March, May, and July) (Sylvan et al., 2006). Likewise, river-influenced waters often exhibited very high N:P ratios (over 50), indicating P limitation of eutrophication during spring and early summer.

Although N limitation occurs in late summer and early fall, the rates of primary productivity are five times lower during this period than in spring (Lohrenz et al., 1999a, 1999b). Sylvan et al. (2006) concluded that P limitation in spring and summer was probably due to increasing N loading in the past 50 yr. As mentioned above, pasturelands are believed to be the source of the greatest amount of P in the Gulf of Mexico (NRC, 2009).

Although there are scant data on N and P losses via groundwater leaching from pastures, it is generally accepted that most N losses occur as nitrate leaching, whereas most P losses from pastures are due to surface runoff during storm events. Hence, best management practices for reducing P loss should focus on those that are aimed at reducing losses in surface runoff, whereas those for N should focus on reducing losses as leaching. The exception would be for pastures on sandy soils, in which case P losses from leaching would also be high.

### Groundwater Contamination

Nitrate ( $\text{NO}_3$ ) is the most soluble form of N and leaching can lead to elevated

$\text{NO}_3$  levels in groundwater. Legal levels of  $\text{NO}_3\text{-N}$  in drinking water are  $10 \text{ mg L}^{-1}$  (USEPA), because higher concentrations can cause methemoglobinemia (blue-baby syndrome), a potentially fatal blood disorder in infants under 6 mo old. Groundwater contamination of  $\text{NO}_3$  under pasture and hayland can occur from both inorganic-N fertilizers and from manure applications. However, because economic returns from hay or pasture are often lower than for row crops, overfertilization of N with commercial fertilizers is less likely than with manure, especially in areas of concentrated poultry or livestock production (Ritter and Chirnside, 1987; Kingery et al., 1993).

Pastures with a long-term history of poultry litter applications had much higher  $\text{NO}_3$  levels in the soil profile than similar pastures that had not been receiving litter (Kingery et al., 1993). Marshall et al. (2001) found an average of 43% of manure N was taken up by plants in typical tall fescue pastures fertilized with poultry litter and concluded that of the remaining 57%, only 6% was lost via denitrification and  $\text{NH}_3$  volatilization. Yet, in certain soils,  $\text{NO}_3$  levels in groundwater at 1 m often exceeded  $10 \text{ mg N L}^{-1}$ . These results are consistent with Adams et al. (1994), who found groundwater  $\text{NO}_3$  levels could exceed the EPA threshold following litter application rates of  $20 \text{ Mg ha}^{-1}$ , but remained below the critical level when application rates were below  $11.2 \text{ Mg ha}^{-1}$ . Similarly,  $\text{NO}_3$  concentrations were less than the legal level in groundwater from fields fertilized with poultry litter at moderate rates (Moore et al., 2000).

Groundwater  $\text{NO}_3\text{-N}$  levels exceeded  $100 \text{ mg L}^{-1}$  for most of the year in two 4-ha fields used for winter loafing areas for 250 cows, stocked at  $31 \text{ cows ha}^{-1}$  on a dairy farm in NW Arkansas. This level of  $\text{NO}_3\text{-N}$ , which exceeds the EPA standard by ten-fold, may pose a significant health risk to humans if drinking water wells are located near the field. Calculations based upon N excretion rates per cow of  $0.23 \text{ kg N day}^{-1}$  (USDA-NRCS, 2008) indicated that daily direct deposits of N were equivalent to  $7 \text{ kg N ha}^{-1}$ . Based on using the area for 3–4 mo, the direct deposits during the winter were in the range of  $620\text{--}820 \text{ kg N ha}^{-1}$ . During warmer months the producer

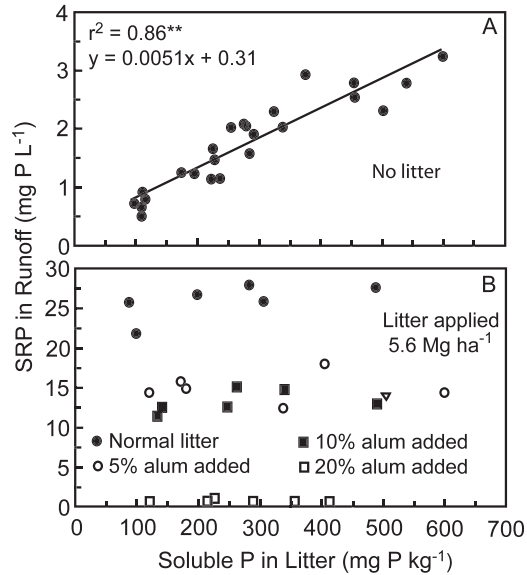
used these same fields as spray fields for effluent applications from his holding pond, with an average annual application of 280 kg N ha<sup>-1</sup>. Hence, the annual total-N loading to the fields was probably between 900 and 1100 kg N ha<sup>-1</sup> (Moore and Brauer, 2009). More research is needed to develop process-based models that can predict groundwater losses given known nutrient loadings, soil properties, and climate.

### Management Strategies for Improving Water Quality

Best management practices for improving water quality associated with pastures can be of two types: 1) measures of nutrient source control, and 2) measures of nutrient transport control. Source control measures are practices that affect nutrient management planning, such as determining fertilizer or manure rates, timing and method of application, nutrient solubility, crop uptake, manure testing, soil testing, and manure treatments. Transport control measures are basically practices that reduce nutrient transport from the field such as proper grazing management, buffer strips, fencing, and other physical control structures.

### Nutrient Source Control

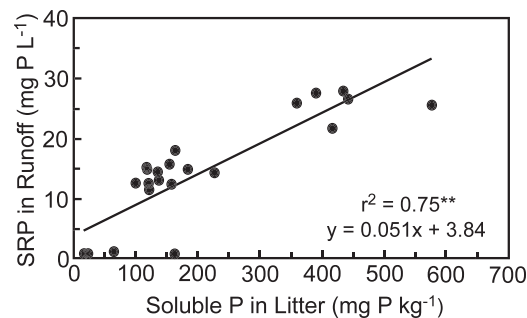
**Nutrient Management Planning.** Prior to the 1940s, farms tended to be somewhat self-sufficient with respect to nutrients. Manure produced by animals was returned to the land on the same farm to meet crop requirements. This recycling of nutrients resulted in a more sustainable agricultural system than most current animal production systems, which often rely on import of grain produced in other areas of the country. By the 1990s, states responsible for finishing the majority of U.S. animals imported over 80% of the grain for their feed (Lanyon and Thompson, 1996). This disconnect in the nutrient cycle has resulted in transfer of nutrients, like P, from grain-producing areas to animal feeding areas causing P accumulation in those soils. Nutrient imbalances on animal farms can be worse where pastures exist, because most nutrients, like P, tend to be recycled within the system when consumed by grazing animals. Many of the vertically integrated animal production enterprises, such as the poultry industry, have developed in areas where land is not suitable to row-crop production and,



**FIGURE 5.2.** Effects of Mehlich III soil-test P on soluble-reactive P (SRP) in runoff water before (A) and after (B) litter application. Different rates of alum were added to the litter. Adapted from DeLaune et al. (2004a).

at least partially, where there is availability of lower-cost agricultural labor (Strausberg, 1995). The result is that the poultry industry is more concentrated where pastureland is the dominant agricultural land use.

Soils with elevated soil-test-P levels can contribute P in runoff in both dissolved and particulate forms (Sharpley, 1995; Pote et al., 1999a). Concentrations of P in runoff from pastures are highly correlated to soil-test-P levels (Sharpley, 1995; Pote et al., 1996, 1999a, 1999b; DeLaune et al., 2004a, 2004b; Schroeder et al., 2004). But this



**FIGURE 5.3.** Effects of amount of soluble P in applied litter and soluble-reactive P (SRP) in runoff water. Adapted from DeLaune et al. (2004a).

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Best management practices for improving water quality....can be of two types:  
1) measures of nutrient source control, and  
2) measures of nutrient transport control.”



...poultry litter, particularly alum-treated litter, might be a more sustainable fertilizer than ammonium nitrate.”

relationship only holds for pastures that have not been fertilized, and the relationship is site specific (Sharpley, 1995; Pote et al., 1996) making it difficult to delineate soil-test–P levels above which P-runoff losses are unacceptable.

When manure or commercial P fertilizers are applied to pastures, there is no significant relationship between soil-test P and P runoff (Sharpley et al., 2001b; DeLaune et al., 2004a). Instead, P losses from fertilized pastures are a function of the amount of *soluble P* applied through manure or commercial P fertilizer (Fig. 5.2). Soluble P is elevated in runoff from pastures fertilized with manure, often for a year or more after application. Dissolved-P values in runoff from pastures fertilized with poultry litter decreased slowly during the 19 mo after application before leveling out to a low rate (Pierson et al., 2001).

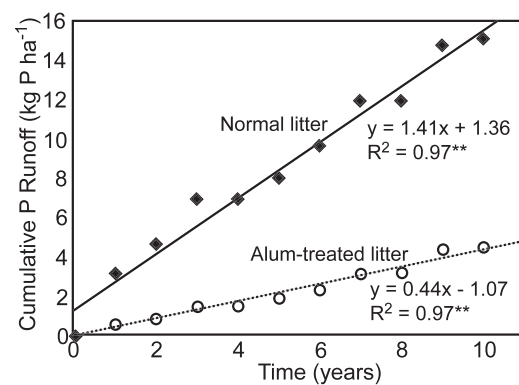
The most important factor affecting P runoff from pastures is the amount of water-soluble P applied as either commercial fertilizer or manure (Shreve et al., 1995; Moore et al., 2000; Sharpley et al., 2001b; Kleinman et al., 2002a, 2002b; DeLaune et al., 2004a, 2004b) (Fig. 5.3). Accurately accessing the potential for organic-P sources to contribute to P runoff requires an accurate measurement of soluble-P in manure. Until recently, the standard method of determining water-extractable P (WEP) from manure has been a 1:10 (manure:water) extraction (Self-Davis and Moore, 2000). However, recent work by

Kleinman et al. (2002b) indicated there is a better relationship between P runoff and WEP in manure if a wider extraction ratio (1:100, manure:water) is utilized.

As mentioned above, most P in runoff from pastures fertilized with animal manure is dissolved P. Hence, Moore and Miller (1994) hypothesized that P runoff from pastures could be reduced if soluble P in manure was precipitated using Al, Ca, or Fe amendments. Alum treatment of poultry litter reduced P runoff from tall fescue plots as much as 87% compared to untreated litter (Shreve et al., 1995). Also, forage yields and N uptake by tall fescue receiving alum-treated litter were significantly higher than for areas receiving untreated litter, probably because alum applications reduced  $\text{NH}_3$  emissions from litter, which improved the fertilizer value (Moore et al., 1995a, 1996). Alum reduced P runoff from small watersheds by 75% over a 10-yr period (Fig. 5.4) and reduced P leaching compared with untreated litter (Moore and Edwards, 2007). These environmental benefits led the USDA-NRCS to make the use of alum a conservation practice standard (USDA-NRCS, 2009).

In a long-term study using small plots, forage yields were 6% greater with alum-treated litter than with untreated litter, and 16% greater than with an equivalent rate of ammonium nitrate (Moore and Edwards, 2005). Higher yields with alum-treated litter were attributed to the greater N availability, due to less  $\text{NH}_3$  loss. Ammonium nitrate resulted in soil acidification and high exchangeable-Al levels in the soil by year 7. In contrast, soil pH increased with both alum-treated and nontreated poultry litter, resulting in lower levels of exchangeable Al than in the nonfertilized control. Aluminum uptake by tall fescue and Al runoff were not affected by fertilizer treatment. They concluded that poultry litter, particularly alum-treated litter, might be a more sustainable fertilizer than ammonium nitrate.

Fertilizer application rate, nutrient solubility in fertilizer or manure, application timing, and application method all influence nutrient runoff from pastures. The largest factor is fertilizer application rate; increasing rates result in more runoff of N and P (Edwards



**FIGURE 5.4.** Cumulative P loads in runoff from paired watersheds fertilized with alum-treated and normal litter. Adapted from Moore and Edwards (2007).

and Daniel, 1992a, 1992b; DeLaune et al., 2004a).

Timing of manure and fertilizer applications can also significantly affect the magnitude of nutrient runoff losses (Westerman and Overcash, 1980; Edwards and Daniel, 1993; Sharpley, 1997; DeLaune, 2002; DeLaune et al., 2004a). Concentrations of P in runoff from tall fescue plots decreased exponentially when the first runoff event occurred on the day of application ( $18 \text{ mg P L}^{-1}$ ) or was delayed for 49 d ( $3 \text{ mg P L}^{-1}$ ) (DeLaune, 2002). Concentrations of P in runoff were as high as  $86 \text{ mg P L}^{-1}$  on the day of fertilizer application and also showed an exponential decrease in concentration with time after fertilizer application (Owens and Shipitalo, 2006). One storm occurring soon after manure application accounted for the majority of the annual P load in runoff from a pasture (Edwards et al., 1996). Others have found similar results (DeLaune et al. 2004a; Schroeder et al., 2004).

Highest losses in runoff occur when manure applications are made during periods of the year when nutrient uptake is slow or the soil is frozen (Sharpley et al., 1998). Incorporation of poultry litter on perennial pasture with the use of a knifing technique reduced P and N losses by 95% (Pote et al., 2003). These findings were verified by Sistani et al. (2009), who also showed that losses of an indicator organism (*Escherichia coli*) in runoff were 100 times higher from plots when litter was broadcast on the surface compared with incorporation into the soil.

Most states do not allow application of manure within a certain distance of sinkholes and wells to prevent drinking water from being contaminated with pathogens,  $\text{NO}_3$  and/or metals. Although we did not find any published research to support these setbacks, it is understood by the scientific community that such contamination is likely to occur without these measures.

**Phosphorus Index.** In 1999 the USDA and EPA developed a joint nutrient management strategy that called for comprehensive nutrient management plans for animal-feeding operations (AFOs) by the year 2008

(USEA and USEPA, 1999). The policy states that in fields where P losses are a problem, the management plan should be based on P content rather than N content of the manure. Each NRCS state office was given three management options for land application of P: 1) managing P based on agronomic levels, which are based on crop need, 2) managing P based on an environmental soil-test threshold, or 3) managing P with the use of the P-index approach (USDA and USEPA, 1999).

Although two of the three strategies rely on soil-test-P measurements, it is generally accepted by the scientific community that approaches using the agronomic or environmental soil-test-P threshold provide a poor assessment of risk of P runoff, because many other variables, like P transport, affect P losses from fields (Sharpley et al. 1996; Sims, 2000; Sharpley et al. 2001a; DeLaune et al., 2004b). For example, Pote et al. (1996) measured P loads of 0.05, 0.16, and  $0.35 \text{ kg P ha}^{-1}$  in runoff from plots with very similar soil-test-P levels ( $285\text{--}295 \text{ mg P ha}^{-1}$ ) (Sharpley et al., 2001b, reporting data from the study by Pote et al., 1996, although these data are not actually presented in the manuscript). The poor relationship between P loads and soil-test P was attributed to variability in runoff volumes (Pote et al., 1996).

Soil-test-P levels can be extremely high and not cause water-quality problems if leaching and/or surface runoff does not occur from the field. In fact, most of the annual P loads from agricultural lands come from relatively small areas of the landscape (Pionke et al., 1997), demonstrating the need to avoid a simple and universal approach (i.e., one number fits all) to nutrient management on all fields. Even when P transport is taken into account, soil-test P is a good predictor of P runoff only on unfertilized pastures; once manure or commercial P fertilizer has been applied, the soluble P in the applied P overrides P runoff associated with soil-test P (Sharpley et al., 2001a; DeLaune et al., 2004a, 2004b).

Realistic evaluations of potential non-point-source P runoff must consider both P transport (surface runoff, erosion and/or subsurface flow) and P sources (manure, fertilizer, and soil-test P)



...in fields where P losses are a problem, the management plan should be based on P content rather than N content of the manure.”

**TABLE 5.5.** Phosphorus index for assessing the vulnerability of a land unit. The sum of the weighted rating values is used to determine the site vulnerability. Multiply units of tons acre<sup>-1</sup> by 0.446 to give MT ha<sup>-1</sup> and units of lbs acre<sup>-1</sup> by 1.12 to give kg ha<sup>-1</sup>. Taken from Lemunyon and Gilbert (1993).

Site characteristic (weighting)	Phosphorus loss (rating value)				
	None (0)	Low (1)	Medium (2)	High (4)	Very high (8)
Soil erosion (1.5)	Not applicable	< 5 ton acre <sup>-1</sup>	5–10 ton acre <sup>-1</sup>	10–15 ton acre <sup>-1</sup>	> 15 ton acre <sup>-1</sup>
Irrigation erosion (1.5)	Not applicable	Tailwater recovery or QS < 6 for very erodible soils or QS < 10 for other soils	QS > 10 for erosion resistant soils	QS > 10 for erodible soils	QS > 6 for very erodible soils
Runoff class (0.5)	Negligible	Low or very low	Medium	High	Very high
Soil-P test (1.0)	Not applicable	Low	Medium	High	Excessive
P-fertilizer application rate (0.75)	None applied	1–30 lb P <sub>2</sub> O <sub>5</sub> acre <sup>-1</sup>	31–90 lb P <sub>2</sub> O <sub>5</sub> acre <sup>-1</sup>	91–150 lb P <sub>2</sub> O <sub>5</sub> acre <sup>-1</sup>	> 150 lb P <sub>2</sub> O <sub>5</sub> acre <sup>-1</sup>
P-fertilizer application method (0.5)	None applied	Placed deeper than 2 in with planter	Incorporated immediately before crop	Incorporated > 3 mo before crop or surface applied < 3 mo before crop	Surface applied > 3 mo before crop
Organic-P source application rate (1.0)	None applied	1–30 lb P <sub>2</sub> O <sub>5</sub> acre <sup>-1</sup>	31–60 lb P <sub>2</sub> O <sub>5</sub> acre <sup>-1</sup>	61–90 lb P <sub>2</sub> O <sub>5</sub> acre <sup>-1</sup>	> 90 lb P <sub>2</sub> O <sub>5</sub> acre <sup>-1</sup>
Organic-P source application method (1.0)	None	Injected deeper than 2 in.	Incorporated immediately before crop	Incorporated > 3 mo before crop or surface applied < 3 mo before crop	Surface applied to pasture or > 3 mo before crop

Q = flow rate of water introduced into the furrow. S = furrow slope.

in risk assessment. Therefore, it is fortunate that 47 states have opted to use a P index for writing nutrient management plans (Sharpley et al., 2003). These indices account for the risk of P runoff from both source and transport factors.

The P-index, developed by USDA-NRCS to account for risk to water bodies from both P sources and P transport, is a field-scale assessment tool (Lemunyon and Gilbert, 1993). The original P index consisted of an additive matrix of nine site characteristics involving P-source and P-transport factors (Table 5.5). Each of these was weighted numerically, with certain characteristics having a higher weighting factor than others. To obtain a P-index value, the P-loss rating value (Table 5.5) for each site characteristic was multiplied by its weighting factor and all nine characteristics were summed. The authors suggested that modification of the original P-index was needed to reflect local landscape conditions and management practices (USDA Soil Conservation Service, 1994).

Two significant changes have been made to the original P index. First, the relationship between

P source and transport was changed from an additive approach to a multiplicative approach to more accurately reflect a field's vulnerability to P runoff (Sharpley et al., 2003). This approach allows fields that have little or no surface runoff or erosion to have a low P-index, even if soil-test P is extremely high. In the original index (Table 5.5), a field could have a very high P-index even though no surface runoff or transport occurs. Second, the risk of P runoff was more accurately quantified such that the P-index actually predicts edge-of-field P losses (DeLaune et al., 2004a, 2004b; Vadas et al., 2009).

Predictive P indices are much more difficult to develop than one that simply gives a relative ranking of risk, but are infinitely more useful. The biggest problem with P indices that include the relative risk of P runoff is that there is no simple way to test their accuracy. However, a predictive P index can be tested for accuracy by comparing the calculated P-index value to measured P loads from fields where runoff data exist.

In 2001, a P-index for pastures was developed for use in Arkansas only (DeLaune et al., 2004a,

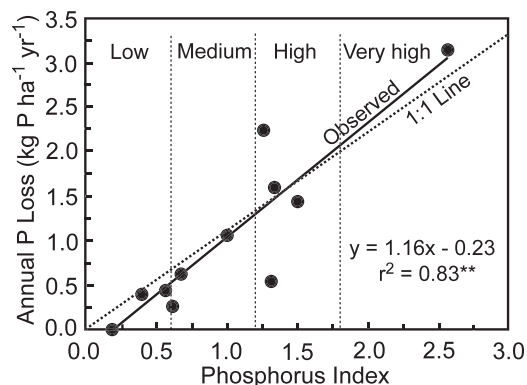
2004b). Although most P indices are developed for row crop agriculture or for all agricultural settings, this index was developed specifically for application of poultry litter to pastures. The multiplicative P index combines the effects of P sources (soil-test P and soluble P applied from manure), P transport (soil erosion, soil runoff class, fertilizer application timing and method, flooding frequency, and grazing management), best management plans (fencing cattle out of streams, filter strips, and terracing), and annual precipitation to predict short-term and annual P loads in runoff (DeLaune et al., 2004a, 2004b). This is one of the few P indices in the USA that actually quantifies the risk of P runoff in terms of predicting the annual P-load in runoff from pastures or fields.

The Arkansas P-index for pastures is based on data from several hundred rainfall simulations on small plots cropped to tall fescue (DeLaune et al., 2004a, 2004b). The research was designed to determine how P runoff from pastures was affected by soil-test P, soluble-P levels in manure, poultry manure application rates, poultry diet modification using phytase and/or corn with high available P, and commercial fertilizer. The weighting factors for P sources were determined by multiple regression analysis from the rainfall simulation studies, where P loads in runoff were modeled using soil-test P and soluble P in manure. Weighting factors were 0.000666 for soil-test P and 0.404 for water-soluble P in manure (with both variables reported in lb P acre<sup>-1</sup>). Commercial fertilizers were not included, based on the belief that their high cost would prohibit overapplication.

Validation data (DeLaune et al., 2004b) showed the P index for pastures predicted edge-of-field P losses from paired watersheds accurately over a 6-yr period, with the slope between observed and predicted losses near one with an intercept near zero (Fig. 5.5). This index works well for pastures in western Arkansas, which typically have silt loam soils, and may work directly or be modified for other areas of the country. The irrigation erosion component present in the original P index developed by Lemunyon and Gilbert (1993) was not incorporated into the P index for pastures developed in Arkansas. Irrigation is typically much more important in row crop situations than in pastures.

**Nitrate Leaching Index.** Leaching of NO<sub>3</sub> through the soil and into groundwater is of concern for human health and the environment. It is impossible to eliminate NO<sub>3</sub> leaching totally (Pratt, 1979), but best management practices such as proper nutrient management can be used to minimize this problem. Some factors that affect NO<sub>3</sub> leaching are similar to those affecting P runoff, including fertilizer and manure application rate (Delgado et al., 1996; Kirchmann and Bergstrom, 2001; Meisinger and Delgado, 2002), type of crop being grown (Delgado et al., 1998a, 1998b) and N content of irrigation water (Bauer et al., 2001).

One tool used for nutrient management planning by NRCS is the NO<sub>3</sub> leaching index (Schaffer and Delgado, 2002). Several NO<sub>3</sub> leaching indices are available that attempt to model leaching as a function of fertilization, climate, soils, crops, and other factors that affect water and nutrient movement in the soil (Pierce et al., 1991; Shaffer et al., 1991; Williams and Kissel, 1991). Although some indices are relatively simple, others are complex and require daily time steps of weather data. As a result, some states like Texas have developed spreadsheets that calculate the N leaching value for the major crops grown in the state. In this case, the leaching index is a relatively simple combination of the percolation index and the seasonal index (USDA-NRCS, 2004).

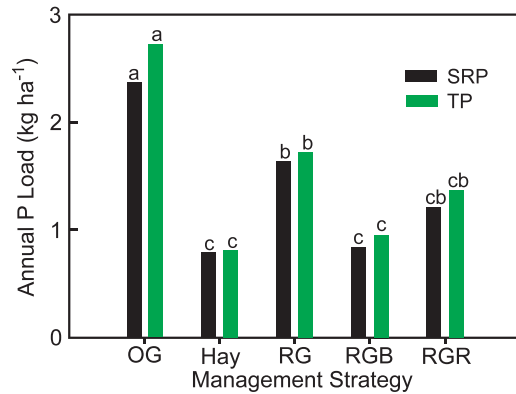


**FIGURE 5.5.** Relationship between annual-P loss in runoff predicted by the P-Index for Pastures (1:1 line) and that observed from small watersheds receiving natural rainfall and annual applications of poultry litter. Adapted from DeLaune et al. (2004b).

“It is impossible to eliminate NO<sub>3</sub> leaching totally, but best management practices... can be used to minimize this problem.”



Phosphorus loads from paddocks harvested mechanically were lower because of reduced runoff volumes compared to grazed paddocks”



**FIGURE 5.6.** Effect of grazing management practices and hay harvest on annual runoff loads of soluble-reactive P and total P from small watersheds (OG = overgrazed, HAY = hayed, RG = rotationally grazed, RGB = rotationally grazed with a buffer strip, RGR = rotational grazed with a riparian buffer strip). Adapted from Pennington (2006).

### Nutrient Transport Control

**Proper Grazing Management.** Runoff and P loss from pastures can be reduced by grazing management practices by affecting soil hydrology and chemical properties of the soil and water (Gifford and Hawkins, 1976, 1978; Van Haveren, 1983; Tollner et al., 1990; Owens et al., 1996; Haan et al., 2003). Rotational stocking can reduce negative soil properties such as soil compaction when compared to intensive continuous stocking, resulting in increased forage yield and vegetative cover (Langlands and Bennet, 1973; Gerrish and Roberts, 1999; Franzluebbbers et al., 2004). Improved forage growth reduces raindrop impact, increases infiltration rates, nearly stops soil erosion, and improves water quality (Duly and Kelly, 1939; Tanner and Mamaril, 1959; Warren et al., 1986a, 1986b; Owens et al., 1989; Owens et al., 1996).

Runoff of P and N were lower from rotationally stocked pastures than pastures that were overgrazed by continuous stocking, whereas runoff losses were even lower for paddocks harvested mechanically (Fig. 5.6) (Pennington, 2006). Phosphorus loads from paddocks harvested mechanically were lower because of reduced runoff volumes compared to grazed paddocks, which had compacted soil (higher bulk density) at the surface (Pennington, 2006; Pennington et al., 2009). Similarly, Sistani et al. (2009) showed

that P and N losses were higher for grazed pastures than for those that were harvested mechanically. Likewise, Schepers and Francis (1982) found nutrient export from pastures increased as grazing intensity increased. However, the effects of grazing intensity on nutrient runoff are relatively minor (Emmerich and Heitschmidt, 2002; Mapfumo et al., 2002; Capece et al., 2007). Capece et al. (2007) and Sistani et al. (2009) concluded that elevated P loads in runoff are probably more related to fertilizer or manure use than to grazing management.

Most grazing studies cited above did not evaluate effects of grazing animals on spatial variability in manure deposition, impacts of animals on stream bank erosion, and/or direct deposits of urine and manure into streams, all of which can increase nutrient transport into aquatic systems (Peterson and Gerrish, 1996; Shirmohammadi et al., 1997; Zaimes and Schulz, 2002). As discussed above, grazing causes compaction, which reduces infiltration and increases runoff. Infiltration rates were lowest along paths made by cattle and areas adjacent to water tanks where animals congregate (Radke and Berry, 1993). Many cow paths lead directly to streams for access to water.

Rotational grazing and intensive grazing are currently gaining greater acceptance in the USA because productivity and profit margins tend to be better compared to continuous grazing (Undersander et al., 1993; Barnhart et al., 1998). Rotational stocking can reduce P runoff compared to continuous grazing (Olness et al., 1980; Ritter, 1988). Rotational stocking also results in more even distribution of manure nutrients compared to continuous stocking in which accumulation of P occurs in areas closest to water sources, shade and feeders (Mathews et al., 1994). A more detailed assessment of the effects of grazing intensity and grazing methods on the environment is in Chapter 3 of this volume.

### Field-Scale Best Management Practices (BMPs).

Currently, the P index for pastures used in Arkansas is being revised (Moore et al., 2009) to include nine field-scale BMPs, for which growers are given credit to reduce P runoff from pastures via use of fencing,

field borders, diversions, ponds, terracing, filter strips, grassed waterways, riparian forest buffers, and riparian herbaceous buffers. The USDA-NRCS conservation practice standard numbers for these BMPs are 382, 386, 362, 378, 600, 393, 412, 391, and 393, respectively (USDA-NRCS, 2009).

Buffer strips or filter strips along a field boundary reduce nutrient runoff by providing a deposition area for sediments, providing an area for infiltration and adsorption of soluble pollutants (Chaubey et al., 1994) and, in some cases, promoting biogeochemical transformation of nutrients to inert forms. In most cases, vegetated buffer strips reduce both sediment and nutrient transport from pastures (Chaubey et al., 1994, 1995; Owens et al., 1996; Blanco-Canqui et al., 2004; Lowrance and Sheridan, 2005; Pennington, 2006). Vegetated buffer strips greatly reduced soluble-P and total-P concentrations in runoff from pastures fertilized with poultry litter (Fig. 5.7).

Riparian buffers have been touted as one of the most important factors for reducing non-point-source pollution in the USA (Gilliam, 1994). Strategically located, they can trap particulate-P and transform N compounds to inert  $N_2$  gas. Cooper et al. (1995) indicated that riparian areas could be sources or sinks for P, because their assimilation capacity is finite. Although most publications indicate that vegetated buffer strips improve water quality, Stutter et al. (2009) found evidence indicating that the strips may have enhanced rates of soil-P cycling, resulting in higher levels of soluble P in the soil and greater P leaching into adjacent water bodies. Fiener and Auerswald (2009) found grassed waterways had little or no effect in reducing soluble-P movement from fields.

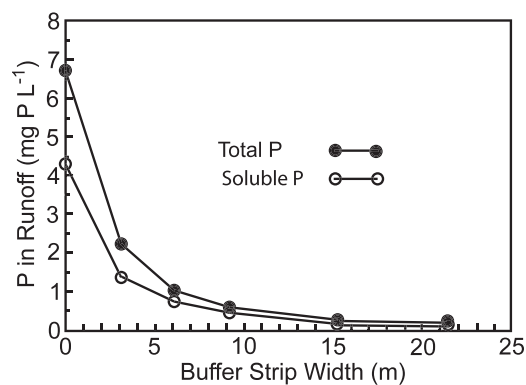
Keeping livestock out of waterways, especially during warm periods of the year, can reduce nutrient runoff from pastures. Cattle are 50 times more likely to defecate while standing in water than when on dry land (Davies-Colley et al., 2002). Fencing livestock from streams, a simple BMP, decreases nutrient and pathogen transport by reducing direct deposits of feces and urine into streams (Nelson et al., 1996; Shirmohammadi et al., 1997; Line et al., 2000). Fencing coupled with tree planting

(i.e., riparian forested buffer) reduced P loads from pastures by as much as 76% (Line et al., 2000). Likewise, providing alternative watering sources, such as troughs and ponds, reduces direct nutrient deposition to streams. When given the choice, compared with a stream, cattle preferred drinking from a watering trough 92% of the time (Sheffield et al., 1997).

### Summary

There is wide disparity among P indices in the southern USA (Osmond et al., 2006). When P-index ratings for pastures were compared with a Mehlich-3 value of 75 mg P  $kg^{-1}$  receiving 9 Mg  $ha^{-1}$  poultry litter, Osmond et al. (2006) found five states gave a low rating (GA, LA, MS, NC, and SC), two states a medium rating (AL, FL), four states a high rating (AR, KY, TN, and TX) and one state with a very high rating (OK). In at least four states the P indices would allow application of 18 Mg  $ha^{-1}$  of poultry litter, even when buffer strips were not used. Most of these indices are not predictive and have not been adequately verified by science. It is not possible to determine which are reliable and which are not.

Policy makers with NRCS are now considering using an environmental soil-test-P threshold to give more consistency to manure application practices allowed by various state-P indices. Currently, some states allow high manure application rates regardless of soil-test P and/or other field conditions (Osmond et al., 2006). It



**FIGURE 5.7.** Effect of vegetative buffer strip width on concentrations of soluble P and total P in runoff water from pastures fertilized with poultry litter. Adapted from Chaubey et al. (1994).

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In most cases, vegetated buffer strips reduce both sediment and nutrient transport from pastures.”

“

The best solution...is...a national P-index for application of fertilizers and manures for pastures and haylands”

is clear the soil-test-P threshold, a one-size-fits-all approach to nutrient management planning, is inadequate because it does not consider P transport (hydrology) or other factors. In addition, when manure or commercial-P fertilizers are surface applied on pastures, they totally overwhelm any effect of soil-test P on P runoff for 1–2 yr (Edwards et al., 1996; DeLaune et al. 2004a; Schroeder et al., 2004). Although variability in the way various state P indices function is a problem, scientific evidence does not support a soil-test-P threshold approach for pastures and hay fields that receive chemical or organic forms of fertilizer.

The best solution to this problem is to develop a national P-index for application of fertilizers and manures for pastures and haylands, which would likely be more specific for pastures and haylands. This index should quantify P runoff on an annual time step, similar to the P-index for pastures (DeLaune et al., 2004a, 2004b) and the P-index developed by Vadas et al. (2009). The P-index ratings of low, medium, high, and very high should have annual P

loads associated with them, as is done with the P-index for pastures. Although developing the P-index will be a costly and time consuming process, the end product will provide a scientific basis for manure application that will be applicable from state to state.

A major knowledge gap in nutrient management planning for pastures is the lack of data on costs, benefits, and cost effectiveness of various BMPs. At present, agency personnel cannot determine costs to keep a kilogram of P from entering a river or stream with the use of various BMPs. Current methods utilized to determine funding available for cost sharing through EQIP (Environmental Quality Incentives Program) uses little scientific evidence for allocating funds to programs or states. Cost-benefit relationships for sites and regions need to be a part of the process to gain the most ecosystem benefit from the funds allocated to the practice.

Nutrient runoff and leaching from pastures cause water quality impairments such as

Rotational stocking leads to less nutrient runoff from pastures.



eutrophication in both freshwater and saltwater systems. In many cases, high nutrient loads in runoff and high levels of  $\text{NO}_3$  in groundwater are associated with animal manure applications. Nutrient losses and soil erosion from pastures are increased by compaction caused by very intensive grazing, which decreases infiltration and increases surface runoff.

Strategies for improving water quality from pastures can be categorized as nutrient source controls or nutrient transport controls. Methods to reduce nutrient sources include practices such as determining proper rates, timing and methods of application of fertilizers or manures, reducing nutrient solubility through manure treatments such as alum, determining realistic crop yields, and using appropriate methods for manure and soil testing. Measures affecting transport of nutrients from the field include BMPs like proper grazing management, buffer strips, fencing, terracing and ponds.

Current P indices utilize information on P sources and transport, along with site characteristics, to determine the risk of P runoff from pastures or crop fields (Osmond et al., 2006). Although some P indices predict edge-of-field P losses, most do not, making it difficult to determine whether they accurately predict the risk of P runoff. There is a need to develop a national P-index that will accurately predict P losses in runoff over a range of crops and soil conditions. Currently, gross differences exist between P indices of various states that should be reconciled by science and not through use of an arbitrary soil-test–P threshold that does not consider hydrology or other transport factors.

The greatest knowledge gaps with respect to water quality from pastures and hayland involve comparative efficacies of BMPs and their cost effectiveness.

### **PROTECT AIR QUALITY BY REDUCING REACTIVE NITROGEN EMISSIONS AND THE FORMATION OF ATMOSPHERIC PARTICULATES**

Loss of N from agricultural to aquatic ecosystems and the atmosphere is a great

economic, ecological, and human health concern (Vitousek et al., 1997; Goolsby and Battaglin, 2001; Galloway et al., 2008; Schlesinger, 2009). When applied to agroecosystems but not removed in livestock or crop biomass the surplus N performs no beneficial agronomic function (Jarvis and Ledgard, 2002). Estimates of surplus N in grazed temperate grasslands range from 30% to 50% of N inputs (Carran and Theobald, 1995; Ledgard, 2001), which include N from fertilizer, exogenous manure, biological fixation, and atmospheric deposition.

Gaseous losses of reactive N as either nitrous oxide ( $\text{N}_2\text{O}$ ), nitric oxide (NO), or ammonia ( $\text{NH}_3$ ) lead to global, regional, and local environmental problems, respectively (Robertson et al., 2000; Mosier, 2001). Nitrous oxide is a stable greenhouse gas in the lower atmosphere that has been linked to climate change. In the upper atmosphere,  $\text{N}_2\text{O}$  is involved in reactions that deplete the protective ozone ( $\text{O}_3$ ) layer (Crutzen, 1970). In the lower atmosphere NO leads to  $\text{O}_3$  formation with negative human health consequences at the regional level. Volatilized  $\text{NH}_3$  typically returns to the terrestrial environment within a kilometer of its source, possibly adding to eutrophication of the downwind sink. Ammonia is a strong base whose atmospheric concentrations are highly correlated with a strong odor (Pain and Misselbrook, 1991).

### **Pathways and Mechanisms of Gaseous N Loss From Pastures and Hayland**

Anoxic soil conditions occur when the pore spaces become filled with water, with maximum rates of denitrification occurring at 60–80% water-filled pore space (WFPS). Hence, physical characteristics of the soil are a strong determinant of denitrification. Soils that are high in clay and poorly drained generally have more denitrification than sandy soils with good drainage. Emissions of  $\text{N}_2\text{O}$  occur only where denitrification is incomplete (i.e.,  $\text{NO}_3$  is not reduced completely to  $\text{N}_2$ ) and a variety of factors, including WFPS, availability of labile C, and availability of  $\text{NO}_3$  influence this process.

Given these abiotic controllers, it is clear that management exerts a strong influence on denitrification. In particular, N amendments,



Strategies for improving water quality from pastures can be categorized as nutrient source controls or nutrient transport controls.”



it is desirable to retain as much N as possible in the agroecosystem for future primary production and to minimize the need for N inputs.”

soil disturbance, and compaction have strong direct effects, mainly through chemical and physical alteration of soil conditions. Management that influences plant productivity constitutes an indirect effect by altering the abundance of organic matter as a C source for denitrification. Even in the absence of management that stimulates  $N_2O$  fluxes (e.g., additions of N or water via fertilizer application, irrigation, or grazing), significant background levels of  $N_2O$  are exchanged between soils and the atmosphere in grasslands. For many years it was believed that  $N_2O$  was only emitted as a result of denitrification, but recent evidence points to significant levels of  $N_2O$  transfer from the atmosphere into soils under highly reducing conditions (i.e., WFPS > 90%) (Neftel et al., 2007). Conversely, anoxia can be found within aggregates and biofilms in soils that are not saturated, so some  $N_2O$  exchange occurs even when bulk soils are relatively dry (e.g., see Neftel et al., 2007).

Because  $N_2$  is nonreactive and constitutes about 78% of the atmosphere, it is often ignored in measurements of denitrification. From an environmental perspective, it is considered to be the most benign loss of N that would otherwise be used by forages or pasture plants. Although  $N_2$  can be fixed by legumes into useful form for return to the crop and soil, from an agronomic perspective, it is desirable to retain as much N as possible in the agroecosystem for future primary production and to minimize the need for N inputs.

Volatilization describes the loss of soil-solution N to the atmosphere from the conversion of  $NH_4$  to gaseous  $NH_3$ . This reaction occurs at pH > 7.5. In more acidic conditions N in the  $NH_4$  form is favored over that in  $NH_3$ , which reduces the likelihood of conversion and volatilization. Once formed, most  $NH_3$  loss to the atmosphere is by diffusion, which is enhanced by coarse soil texture, low soil water content, high temperature, and high wind speed (i.e., the drivers of evaporative demand). As  $NH_3$  becomes airborne, it either quickly dissolves in water, forming  $NH_4$  that can be taken up directly by leaves or be redeposited to soil, where it is available for biotic uptake (Asman et al., 1998; Ferm, 1998; Aneja et al., 2001).

### Conservation Management Practices Affect Gaseous N Loss

Alternative grazing and forage systems affect  $NH_3$  emissions directly by altering vegetation structure and growth. Plant species differ in their ability to absorb or emit  $NH_3$  (McGinn and Janzen, 1998), so forage species composition could affect atmospheric  $NH_3$  concentrations. Grazing ruminants respond to a variety of dietary (e.g., forage N content and degradability) and metabolic factors (e.g., growth promoters, lactation) that affect production of urea, its recycling to the digestive tract, and its excretion in urine.

The nutrient management practice standard (590), which is identified for both  $N_2O$  and  $NH_3$  loss, calls for managing the amount, source, placement, form, and timing of the application of plant nutrients and soil amendments. Below we review the scientific support based on research conducted on U.S. pastures and haylands. The *Web of Knowledge All-Database* searches (input terms were pasture,  $N_2O$ , NO,  $NH_3$ ) located 47 studies of  $N_2O$ , NO, or  $NH_3$  fluxes from nonrangeland pastures, but only 7 were based in the USA. Five of these were conducted on bermudagrass pastures and two on pastures dominated by tall fescue.

### N Inputs

In general, pasture applications of inorganic N consist of ammonium nitrate or ammonium sulfate that are spread in a relatively uniform manner with mechanical devices. Typical recommendations for temperate pastures are 50–100 kg N ha<sup>-1</sup> yr<sup>-1</sup> split into early spring and early fall applications to supply nutrients just prior to rapid growth periods. Organic N comes from grazing animals directly as excreta, as manure removed from confined animal areas, or as solid-phase urea (Saggar et al., 2004). Manure, spread mechanically, is distributed more uniformly on the land area than direct excreta, but the actual uniformity depends on the liquid–solid ratio of the manure that changes dispersion properties, which can be quite variable. Nitrogen inputs from excreta and the subsequent effects on N losses to the atmosphere are extremely patchy at scales from centimeters (Koops et al., 1997) to hundreds of meters (Jackson et al., 2007). This spatial heterogeneity makes

it very difficult to quantify N losses to the atmosphere accurately (Groffman et al., 2006).

Gaseous N losses from pastures receiving mineral-N fertilizer were 50% of those from urea fertilizer when applied at the same N rate (Colbourn, 1992; Eckard et al., 2003; Muller and Sherlock, 2004). These authors concluded that the additional  $\text{N}_2\text{O}$  loss from urea was likely from nitrification during N transformation from  $\text{NH}_4$  to  $\text{NO}_3$ , whereas most of the loss from the ammonium nitrate fertilizer was from denitrification. A U.K. study on cool-season pastures showed that total denitrification losses were directly related to N application rate, irrespective of the fertilizer type (Ellis et al., 1998). However,  $\text{N}_2\text{O}$  loss was not solely related to N application rate because the type of N applied modified the response over time; N loss as  $\text{N}_2\text{O}$  was greater from manure slurry than from mineral fertilizer.

Diluting swine manure with water, either during or immediately following application to pastures in Nova Scotia, reduced  $\text{NH}_3$  emissions by 41% and 45%, respectively (Mkhabela et al., 2009). These results align with many others. Other approaches to reducing volatilization such as manure injection are not feasible on intact pastures because the dense sod inhibits mechanical insertion and increases risk from degradation of soil organic matter and forage productivity. Direct  $\text{N}_2\text{O}$  losses were not affected by several management treatments, but indirect  $\text{N}_2\text{O}$  loss was a large pathway (Mkhabela et al., 2009).

Emissions of  $\text{N}_2\text{O}$  from pasture soils to the atmosphere generally peak soon after N application (Hutchinson and Brame, 1992; Thornton et al., 1998; Sullivan et al., 2005; Bender and Wood, 2007; Tiemann and Billings, 2008), but waned within a few days. Only one article reported that N inputs from broiler litter did not result in increased  $\text{N}_2\text{O}$  emissions (Marshall, 1999). In some cases, applied N did not increase  $\text{N}_2\text{O}$  emission above control plots until subsequent rain occurred (Hutchinson and Brame, 1992). The sum of these pulsed losses always accounted for only 0.3–5% of the N applied. Levels of  $\text{N}_2\text{O}$ –N losses were roughly equivalent to the 1–6 kg N

$\text{ha}^{-1} \text{ yr}^{-1}$  entering eastern U.S. ecosystems via wet and dry deposition each year (<http://nadp.sws.uiuc.edu/>).

Of the studies cited above, only Thornton et al. (1998) and Hutchinson and Brame (1992) measured NO fluxes on pastures, which were greater with N amendments than without. However, Thornton et al. (1998) found < 0.4% of N applied was lost as NO–N, while Hutchinson and Brame (1992) estimated 3.2% of applied N was lost. In contrast, Sullivan et al. (2003) estimated 8–31% of the N applied as swine effluent was emitted from soils as  $\text{NH}_3$ .

### Effects of N Form on Gaseous N Loss

Two U.S. studies explicitly compared N emissions after organic- and inorganic-N amendments to pastures (Sullivan et al., 2005; Bender and Wood, 2007). With equal N application rates of  $\sim 112 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ,  $\text{N}_2\text{O}$  emitted from pastures receiving swine effluent was double that from ammonium nitrate, which represented about 2% of the total N applied (Sullivan et al., 2005). Bender and Wood (2007) found that 2–3% of the N applied as swine effluent was lost via gaseous emission, whereas < 1% of applied N was lost from pastures receiving ammonium nitrate. Emissions of  $\text{N}_2\text{O}$  and NO were lower when composted poultry litter was applied than when fresh poultry litter or urea was applied, but emissions for all treatments were  $\leq 1\%$  of the N applied. From the eight studies, highest  $\text{NH}_3$  losses occurred (8–31% of N applied) when liquid swine effluent was supplemented with ammonium nitrate at  $112 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  (Sullivan et al., 2003). These studies indicate that  $\text{NH}_3$  volatilization is the pathway of greatest gaseous N loss in pasture/hayland systems.

### Timing of N Application Effects on Gaseous Loss of N

Bender and Wood (2007) showed that  $\text{N}_2\text{O}$  emissions spiked in the days immediately following application of swine effluent, but returned to background levels within 4–16 d. In contrast to ammonium-nitrate-amended soil, emissions from swine-effluent-amended soil were always greater from lighter than from heavier textured soils. On soils with high clay content,  $\text{N}_2\text{O}$  emissions were similar



These studies indicate that  $\text{NH}_3$  volatilization is the pathway of greatest gaseous N loss in pasture/hayland systems.”



Losses of gaseous N from pastures to the atmosphere are generally  $\leq 5\%$  of the N applied.”

from swine effluent and ammonium nitrate amendments. No U.S. literature was found on season-of-application effects on gaseous N losses. Extensive New Zealand research shows nitrification inhibitors such as dicyandiamide (DCD) significantly reduced  $\text{N}_2\text{O}$  emissions from pasture (e.g., Di and Cameron, 2006).

### **Defoliation and Compaction Effects on Gaseous Loss of N**

Disturbances such as grazing, harvest for hay, and burning are likely to influence gaseous N loss by affecting the amount of plant biomass, soil N, water-filled pore spaces, and soil temperature (Livesley et al., 2008; Uchida et al., 2008). About 40–80% of cattle excreta N is in urine, of which 10–95% is in the form of urea (Rodhe et al., 1997). Contact with water and the enzyme urease, which is found universally in feces and soils (Hoult and McGarity, 1986), causes rapid conversion of urea to gaseous  $\text{NH}_3$ . Excretion of urine by livestock creates hot spots where concentrated N combined with high water-filled pore spaces results in significant  $\text{N}_2\text{O}$  loss from nitrification, denitrification, or both (Lovell and Jarvis, 1996; Ambus et al., 2007).

Depending on weather conditions and existing plant cover, which both affect urease activity and the ability of leaves to take up volatilizing  $\text{NH}_3$ , more than 60% of the urine N can be volatilized to  $\text{NH}_3$  (Ryden et al., 1987). Other estimates range from 10% to 90% (Woodmansee, 1978; Rotz et al., 2005) where dry conditions and low canopy volume generally contribute to  $\text{NH}_4$  loss. Ammonia losses may be highest on medium-textured soils, because sandy soils result in more and quicker infiltration and heavier soils have greater cation exchange capacity (Whitehead and Raistrick, 1993). Greater standing plant biomass slows wind speed and allows greater plant absorption of the  $\text{NH}_3$  volatilized from urine patches (Sommer and Hutchings, 2001).

Uchida et al. (2008) experimentally applied urine to soils with a range of aggregate size classes that had been packed to four levels of density. Emissions of  $\text{N}_2\text{O}$  during 30 d were similar among aggregate sizes if the soils were not packed. When packed, columns with small soil aggregate classes ( $< 1$  mm) emitted

more than columns with larger aggregate size classes. Colbourn (1992), using repacked soil cores, concluded that soils receiving no N inputs as urine or fertilizer emitted about  $3 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  of  $\text{N}_2\text{O}$ , whereas soils receiving urea or ammonium nitrate at  $200 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  emitted about  $20 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ .

On grazed cool-season pastures in eastern Kansas,  $\text{N}_2\text{O}$  emissions of about  $20 \text{ mg N m}^{-2} \text{ d}^{-1}$  occurred when fertilized with ammonium nitrate whereas hayed plots fertilized the same had significantly lower  $\text{N}_2\text{O}$  emission (Tiemann and Billings, 2008). This was attributed to reduced soil organic-C availability (i.e., reduced capacity for denitrification) under periodic haying.

### **Plant Species Composition Effects on Gaseous Loss of N**

The species mixture of a pasture community affects N dynamics directly, primarily via  $\text{N}_2$  fixation by legumes (Ledgard, 2001). Furthermore, legumes and nonlegumes differ in their capacity to absorb soil N (Ridley et al., 1990). In some cases the presence of pasture legume species increases  $\text{N}_2\text{O}$  emissions (Niklaus et al., 2006), whereas there was no effect on emissions due to legume management in Australian temperate pastures (Livesley et al., 2008). No U.S. literature was found addressing this topic on pastures.

### **Dietary Manipulation Effects on Gaseous Loss of N**

Manipulating the quantity and quality of excreta via dietary factors may be a useful approach to mitigating N loss from agroecosystems. For example, hippuric acid in the urine of livestock inhibits denitrification as much as 50% (Kool et al., 2006; van Groenigen et al., 2006). However, adding tannin to the cattle diet on rangelands of the northern Great Plains did not reduce  $\text{N}_2\text{O}$  flux from soils, even though the urine contained only half the N (Liebig et al., 2008). No literature was found addressing this topic on humid pastures of the USA, where the higher soil water content would be expected to increase emissions.

### **Summary**

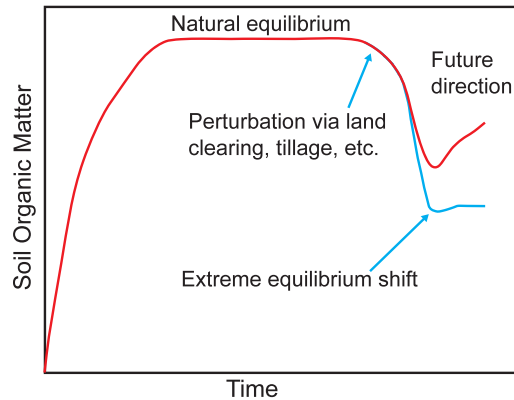
Losses of gaseous N from pastures to the atmosphere are generally  $\leq 5\%$  of the N

applied. There is strong literature support that  $N_2O$  emissions are stimulated by N inputs and some support for increased  $NO$  and  $NH_3$  losses with increased rates of N applications to pastures. There is modest support that organic sources of N promote greater gaseous N loss than does inorganic fertilizer N. No U.S. research was found on the effects of timing of N applications, species composition, or dietary factors on gaseous N loss from pastures. Some evidence exists that haying reduces gaseous N loss from fertilized cool-season pastures.

Significant regional gaps exist in the U.S. literature, because most support for the hypotheses above is from research conducted in the southern USA, mainly on warm-season pastures. This contrasts with western Europe, New Zealand, and Australia, where management effects on N dynamics of cool-season pastures have received two orders of magnitude more attention. Soil characteristics, management peculiarities, and climatic differences certainly will limit extrapolation from these data to the USA. Nonetheless, important principles and subjective generalizations from this vast literature should apply to pastures globally.

### MAINTAIN OR IMPROVE THE PHYSICAL, CHEMICAL, AND BIOLOGICAL CONDITION OF THE SOIL

The scientific literature is replete with examples of the nutrient-supplying benefits of inorganic fertilizers, manures, and organic by-products to short-term production of pasture and hay crops. Yet over the long term, application of these nutrient sources may also influence soil physical, chemical, and microbiological properties that, in turn, affect pasture productivity. Fertilization may improve these soil properties indirectly through increases in soil organic matter (SOM) content resulting from greater productivity of shoots and roots. Soil organic matter content can also be increased directly with application of animal manure. Increasing SOM content via soil management is considered a worthy endeavor owing to its contribution to favorable soil fertility and physical properties. Because of its large role in soil function, SOM content is considered to be part of a minimum data set that defines soil quality (Doran and Parkin,



**FIGURE 5.8.** Conceptual soil organic matter equilibrium shifts with change in soil management. Time responses (over several years) are estimates to show relationships based on numerous published data sets. Adapted from Wienhold et al. (2004).

1996)

Long-term increases in SOM, which contains the largest terrestrial pool of C (Lal, 2004), can lower atmospheric-C concentration to mitigate climate change. Conversely, long-term application of nutrients, particularly those contained in animal manures and sewage sludges, at high rates may have negative effects on pasture productivity, the environment and on animal/human health owing to soil accumulation and/or escape of waste constituents to water bodies and the atmosphere.

When pastures are established, and then managed consistently, the underlying soil will shift to a new steady-state content of SOM that remains relatively stable through time under a given set of soil state factors (Jenny, 1980). Whether or not this new steady state is an improvement over the initial state depends on previous management or lack thereof (Fig. 5.8), and each soil has a SOM level that depends on climate and vegetation management. Clearing native grass or forestland to establish improved pasture may result in little change or a slightly lowered SOM steady state. However, pasture establishment on lands previously in row crops will likely result in a higher steady state of SOM concentration. In both cases, nutrient management plays a role in establishment of the new SOM equilibrium,

“

When pastures are... managed consistently, the underlying soil will shift to a new steady-state content of SOM that remains relatively stable”



SOM content may be increased via direct additions of organic matter and/or to increases in biomass production.”

and influences the physical, chemical, and biological condition of the soil. The NRCS CPPE matrix (Table 5.2) identified several ways that nutrient management alters soil properties, including: 1) SOM content; 2) contaminants associated with N, P, and K in commercial fertilizer, animal wastes, and other organics; 3) contaminants associated with salts and other chemicals; and 4) soil compaction. Herein we present U.S. research findings regarding these impacts on pasture soils, and identify knowledge gaps in the U.S. scientific literature.

### SOM Depletion

Studies on changes in SOM content owing to management are necessarily long-term, because it takes several years for soil C and N equilibrium shifts to occur and stabilize. Unfortunately, most research grants awarded in the USA are short term (2–3 yr), causing reports on long-term management impacts on soil C and N to be scant. In addition, most U.S. scientific literature on this topic deals with effects of changes in tillage/cropping system or nutrient management, particularly manure sources, in row-crop agriculture. Such studies typically show equilibrium concentrations of SOM increase with reductions in tillage (e.g., Havlin et al., 1990; Wood et al., 1991; Wood and Edwards, 1992), increases in cropping intensity (e.g., Havlin et al., 1990; Wood and Edwards, 1992), and long-term application of manures (Wood and Hattey, 1995). These cropland studies imply that well-fertilized permanent pastures and long-term hay fields should attain higher equilibrium SOM concentrations than row croplands. Several studies outside the USA address these issues for pastures (e.g., Haynes and Williams, 1992; Sparling et al., 1994; Noble et al., 1999; Carran and Theobald, 2000), but little U.S. scientific literature exists regarding nutrient management effects on equilibrium contents of SOM.

The CPPE matrix (Table 5.2) indicates that compliance of the NRCS Nutrient Management Practice Standard (590) should result in slight to moderate improvement in SOM content owing to maintenance or enhancement of biomass production. Liebig et al. (2006), working in North

Dakota, studied long-term (> 70 yr) grazing management impacts on soil variables related to SOM including soil organic C, total N, and particulate organic-matter C and N. Treatments were moderately grazed native vegetation pasture (MGP; 2.6 ha steer<sup>-1</sup>; no fertilizer), heavily grazed native vegetation pasture (HGP; 0.9 ha steer<sup>-1</sup>; no fertilizer), and fertilized crested wheatgrass pasture (FCWP; 0.4 ha steer<sup>-1</sup>; 45 kg N ha<sup>-1</sup> yr<sup>-1</sup> as ammonium nitrate). Soil organic C and N in surface soil (0–5 cm) under FCWP and HGP were greater than that for MGP. The FCWP treatment also had greater amounts of particulate organic-matter C and N to a 30-cm depth than did HGP or MGP. These findings indicate that fertilization with N maintains to moderately increases SOM content over the long term in northern Great Plains pastures.

Similar results for soil organic C and N were obtained in North Dakota by Wienhold et al. (2001) in a study conducted a few km from the Liebig et al. (2006) site and had similar treatments. Results of both experiments support the notion that prescribed grazing (NRCS Practice Standard 528) interacts with nutrient management to influence SOM contents of pasture soils. In contrast with these studies, a study in Florida (Sigua et al., 2006) compared a natural wetland with a 63-yr-old bahiagrass pasture derived from a natural wetland histosol that had been fertilized every third year with 90, 13, and 37 kg ha<sup>-1</sup> of N, P, and K, respectively. The SOM content of the surface soil (0–20 cm) beneath fertilized bahiagrass pasture was only 14% of that under reference wetlands, further emphasizing that direction of shift for the SOM equilibrium depends on initial soil condition. In a short-term study, a one-time application of 841 kg 16–20–0 plus 13% S ha<sup>-1</sup> did not increase soil total N on a meadow renovation project in the Sierra Nevada of California (Kie and Myler, 1987) documenting that equilibrium shifts in components of SOM due to land management treatments may take many years to be expressed.

The SOM content may be increased via direct additions of organic matter and/or to increases in biomass production. After 15–28 yr of broiler-chicken litter (manure, bedding material, wasted feed, and feathers) applications

to 12 tall fescue pastures in Alabama, there was significantly higher soil organic C and N, but lower soil C:N in surface soils (0–15 cm) than those found on matched nonlittered pastures (Kingery et al., 1994). In a short-term study, soil organic C and N of soils were studied under bermudagrass pasture either not fertilized or fertilized annually with ammonium nitrate or broiler chicken litter (Wood et al., 1993). Phosphorus, K, and lime were applied in nonlimiting amounts so only N was limiting. After 2 yr the contents of soil organic C and N were not different at any soil depth, although there was a trend for the broiler-litter treatment to have greater soil C and N concentrations than the ammonium-nitrate and control treatments. The results again suggest that equilibrium in soil organic C and N takes several years to show a measurable change.

Staley et al. (2008), working in West Virginia, conducted the only known U.S. study regarding conversion of deciduous forest to silvopasture and its impacts on SOM. Treatments included a forest (about 60 yr old; no fertilizer), a newly established silvopasture (2 yr old; lime, N, P, and K applied) converted from the forestland, and an established pasture (about 40 yr old; lime, N, P, and K applied). Two years after silvopasture establishment, organic C and N concentrations and C:N in the silvopasture soil (0–15 cm) were intermediate between forest and pasture, indicating rapid and substantial forest litter decomposition. However, soil under silvopasture had greater organic P than either pasture or forest, which the authors attributed to immobilization of fertilizer P with incorporation of forest litter.

These results illustrate that direction of SOM equilibrium shift with new soil management depends on initial soil condition and management, i.e., silvopasture established from deciduous forest lowered SOM content but, at least temporarily, increased concentration of soil organic P. Conversely, one could deduce from this study that establishing silvopasture on established pasture or croplands may indeed increase SOM contents. A study in southeastern Nebraska compared 130-yr-old forest established on pasture (not fertilized), present-day conventional corn–soybean rotation established on pasture (fertilized), and

a never-tilled or fertilized pasture. Contents of soil organic C and total N increased significantly in the order of cropland < pasture < forest (Martens et al., 2003), which supports the findings of Staley et al. (2008).

Nutrient management affects the amounts of SOM and the amounts of microbial-mediated transformations in soil. Nitrogen mineralization and C emission via respiration are the two most commonly studied SOM transformation variables. In North Dakota, N mineralization rate in the upper 5-cm and the 5–15 cm soil layer of soil under fertilized crested wheatgrass was greater than that under nonfertilized native grass pastures (Wienhold et al., 2001). They suggested that immobilized fertilizer N under crested wheatgrass was more easily mineralized than the mature organic N under the native pasture. In addition, numbers of culturable micro-organisms, microbial biomass C, microbial biomass N, ratio of microbial biomass C to soil organic C, and ratio of microbial biomass N to soil organic N were similar among the pastures. This further suggested that differences in N mineralization were due to organic-matter quality rather than differences in microbial activity.

### **Contaminants—N, P, and K in Commercial Fertilizer, Animal Wastes and Other Organics**

Code 590 indicates that proper nutrient application will provide a slight to moderate reduction of contamination risk from N, P, and K. This implies using appropriate N, P, and K rates according to soil-test laboratory recommendations and timing to match crop nutrient needs. Overapplication and/or poor timing can lead to escape of N, P, and K to the environment, which leads to soil, water, and air contamination. Of the three macronutrients N, P, and K, loss of N and P are of greatest concern because they have detrimental off-site water- and air-quality impacts, such as eutrophication of water bodies with dissolved and particulate N and P, NO<sub>3</sub> leaching to groundwater, and NH<sub>3</sub> and emissions of greenhouse gases.

Potassium generally has much lower environmental impact, although when out of balance with other nutrients it can cause grass tetany (hypomagnesaemia) in cattle (Ball et al.,



Of the three macronutrients N, P, and K, loss of N and P are of greatest concern because they have detrimental offsite water- and air-quality impacts”



Phosphorus has no gaseous pathway, which simplifies its nutrient cycle in comparison to N.”

2002). More specifically, high levels of soil K may depress plant uptake of Mg, even if there is adequate soil Mg, which leads to abnormally low levels of blood Mg (Tisdale et al., 1985). High levels of soil ammoniacal N can also depress forage Mg uptake and promote grass tetany (Tisdale et al., 1985). In Alabama, tall fescue pastures receiving long-term poultry litter had a higher ratio of K/(Ca + Mg), which is associated with grass tetany potential, than pastures receiving no litter (Kingery et al., 1993). However, the molar ratio did not exceed 2.2, which is considered the threshold for grass tetany.

When N and P in fertilizers, animal manures, or other waste products are applied in excess of that needed for maximum agronomic yield, or at the wrong time, they have increased risk for escape to the environment. The actual loss of surface applications of N and P can be from that accumulated and perhaps even transformed in the soil or the recently applied materials. Most studies have addressed the buildup of various organic and inorganic forms of soil N and P from applications of animal manures. Much less emphasis has been placed on buildup of these constituents from commercial inorganic fertilizers because they generally are easier to apply at accurate rates and they, unlike animal manures in many cases, are usually considered a direct cost to farmers.

In many areas of the USA, manure generated by concentrated animal feeding operations exceeds local pasture and hayland needs for N and P (Carpenter et al., 1998). Moreover, the bulky and relatively low nutrient concentration of animal manures limits the economic distance they can be hauled (Sharpley et al., 1993). Applications of animal manure N and P that exceed that needed for pasture and hayland production results in buildup of soil N and P. Further, concentrations of N and P in manures usually are not in ratios that match forage needs (Pant et al., 2004). For example, poultry litter applied on an N basis provides excess P to forages, resulting in a buildup of soil P that is subject to loss in surface runoff (Kingery et al., 1993; Sharpley et al., 1993).

Nitrogen can be lost from soil to the environment via  $\text{NO}_3$  leaching, runoff of dissolved and particulate N,  $\text{NH}_3$  volatilization,

and emission of  $\text{N}_2\text{O}$  and dinitrogen ( $\text{N}_2$ ) gas. These processes increase in magnitude as N in fertilizers, animal wastes, and other waste materials are applied beyond forage crop needs. In Georgia, broiler litter was applied for 2 yr to tall fescue pasture at cumulative rates of 0, 2733, 5466, 10,931, and 16,397 kg N ha<sup>-1</sup> (Jackson et al., 1977). The 2733 kg N ha<sup>-1</sup> was far beyond the tall fescue N requirement. They found little difference in soil total N due to litter application rate, and no difference when soil  $\text{NO}_3\text{-N}$  was subtracted from soil total N. They attributed the lack of difference among rates to poor incorporation of litter leaving much N on the soil surface. Soil profile  $\text{NO}_3$  increased with higher rates and successive applications indicating the increased potential for  $\text{NO}_3$  leaching when heavy N rates are applied.

Kingery et al. (1994) used 12 paired tall fescue pastures in the Appalachian Plateau physiographic region of Alabama (average annual rainfall of 1325 mm yr<sup>-1</sup>) that had received long-term (15–28 yr) application of broiler-chicken litter or no litter to determine accumulation of soil total N and  $\text{NO}_3\text{-N}$ . Soil total N under littered pastures was higher than in nonlittered pastures to a depth of 30 cm. Soil total N under littered soils were elevated to 1 m depth without significant accumulations of  $\text{NO}_3\text{-N}$  (about 3 mg kg<sup>-1</sup>) that increased with depth to 3 m (about 45 mg  $\text{NO}_3\text{-N}$  kg<sup>-1</sup>). The data indicated that soils amended with broiler litter were more vulnerable to N-loss via runoff, leaching, and gaseous pathways. The  $\text{NO}_3$  was depleted in upper portions of the soil profiles, but that in excess of tall fescue requirements was leached to the lower profile, representing a threat to groundwater quality. In a similar study on bermudagrass in eastern Oklahoma, 12–35 yr of poultry litter applications averaging 270 kg N ha<sup>-1</sup>yr<sup>-1</sup> increased total N in the upper portion (0–20 cm) of the soil profiles compared with controls (Sharpley et al., 1993). However,  $\text{NO}_3\text{-N}$  did not accumulate deep in the soil profile, suggesting that litter N was not applied in excess of plant needs. Bermudagrass may have greater N uptake potential than tall fescue.

Phosphorus has no gaseous pathway, which simplifies its nutrient cycle in comparison to N. Owing to its sorption to soil, which is affected by the type of surfaces contacted by P in soil

solution (Tisdale et al., 1985), leaching of P to subsurface water occurs in only a few soils. As with N, loss of P increases when P in fertilizers, animal wastes and other waste materials is applied beyond forage crop needs. Runoff losses of P have had much attention in relation to surface application of animal wastes sparking development of the P index for assessing site vulnerability to loss of P (Lemunyon and Gilbert, 1993) and for planning comprehensive nutrient management (Beegle et al., 2000). The index is now used to prevent applications of animal waste that could promote loss of P and N to the environment.

Several studies (Sharpley et al., 1993; Kingery et al., 1994; Lucero et al., 1995; Vervroot et al., 1998; Novak et al., 2000; Sharpley et al., 2004) have shown that application of animal manures to pastures or haylands beyond forage-P requirements builds surface soil-P to high levels. Most of these studies

have long-term (decades) applications of manure, but some (Lucero et al., 1995; Vervroot et al., 1998) show soil-P levels build in only a few years when excess manure P is applied. Soil-P buildup also occurs in areas where grazing animals congregate in pastures (Graetz and Nair, 1995; Sigua and Coleman, 2006). As previously mentioned, part of the reason for soil-P buildup is the disparity in N:P ratios between manure and plant tissue, particularly when manure is applied according to forage-N requirements. Switching from nutrient management of poultry litter based on N to that based on P lowered soil-test levels of available P on high-P soils (Maguire et al., 2008). Nutrient management based on P lessens soil-P buildup where manures are applied, and lowers risk for loss of P to surface waters. But then alternatives need to be used to meet N requirements for grass pastures and hay fields, suggesting the value of legumes in these situations.

Cattle traffic in pastures can lead to erosion that results in loss of nutrients and soil quality.





water-extractable soil P is the preferred analysis if environmental concerns are considered.”

Continuous application of manure alters the amount of soil P, soil-P form, and relative P availability. Sharpley et al. (2004) conducted a comprehensive study involving six grassland sites in New York, eight in Oklahoma, and six in Pennsylvania that received swine slurry, dairy manure, or poultry manure (40–200 kg P ha<sup>-1</sup>yr<sup>-1</sup>) for 10–25 yr. Compared to areas with no manure applied, manure applications resulted in 1) more soil P being in the inorganic form, 2) a shift in P chemistry from Al- and Fe-dominated complexes to Ca minerals with a concomitant increase in soil pH, and 3) a decrease in the proportion of water-soluble P:Mehlich-3 extractable P. This indicates water-extractable soil P is the preferred analysis if environmental concerns are considered.

Phosphorus leaching has not been considered a problem in most mineral soils where soil-test recommendations have been followed, but downward P movement in soil profiles “can occur in deep sandy soils, in high organic matter soils, and in soils where over fertilization and/or excessive use of organic wastes have increased soil-P values well above those required by crops” (Sims et al., 1998). Subsurface movement of P can contribute to eutrophication of surface waters that have a hydrologic connection with shallow water tables. Surface applications of manures to pasture or haylands cause accumulations of extractable P below the soil surface (Sharpley et al., 1993; Kingery et al., 1994; Lucero et al., 1995; Vervroot et al., 1998; Novak et al., 2000). Most of these studies have shown downward movement of P to 30–40-cm depths, but movement can be deeper, especially in sandy soils (Novak et al., 2000). The increase in Mehlich-3 extractable P after 10 yr of swine-effluent applications was reflected in higher dissolved-P concentrations of shallow groundwater.

The downward movement of surface applied manure-P in a Virginia soil with high P-fixation capacity was attributed to mobility of organic-bound P (Lucero et al., 1995), although only inorganic P was measured. Manure-P additions in Oklahoma lowered the P-sorption index (capacity of the soil to absorb P) below that of untreated soils, which allowed downward movement and increases in Bray-extractable P and total P to a depth of 30 cm (Sharpley et al., 1993). This finding, along with those of

Sharpley et al. (2004) regarding the increased ratio of inorganic P:organic P where manures are applied over the long term, suggests that inorganic P moves downward as it fills adsorption sites.

### Contaminants—Salts and Other Chemicals

Salts in fertilizers, manures, or other organic nutrient sources can have negative effects on pasture productivity if they reach excessive levels, generally with soil electrical conductivity (EC expressed as Siemens m<sup>-1</sup>) values > 4 dS m<sup>-1</sup> (U.S. Salinity Laboratory Staff, 1954). Salt injury from commercial fertilizers usually occurs in row crop situations when fertilizer is banded too close to germinating seeds, which is not a factor in pastures where fertilizer is typically broadcast applied. However, long-term application of manures or biosolids at high rates may build soil salts to levels that exceed the 4 dS m<sup>-1</sup> threshold.

The CPPE for the NRCS Nutrient Management Practice Standard (Table 5.2) indicates that decreased application of excess nutrients will result in reduced salts. We found only two studies that considered effects of pasture nutrient management on soil salts. Greater soil electrical conductivity occurred after broiler litter had been applied for 15–28 yr to 12 tall fescue pastures in Alabama compared to matched pastures receiving no litter (Kingery et al., 1994). However, average EC in the upper 60 cm of littered pastures (0.08 dS m<sup>-1</sup>) was well below the 4 dS m<sup>-1</sup> threshold. After more than 70 yr of grazing nonfertilized native vegetation pasture and fertilized (45 kg N ha<sup>-1</sup> yr<sup>-1</sup> as ammonium nitrate) crested wheatgrass pasture, all soil EC values (range = 0.18 to 0.48 dS m<sup>-1</sup>) were well below the 4 dS m<sup>-1</sup> threshold (Liebig et al., 2006). These studies suggest that salt contamination is of limited importance in moderately fertilized pastures.

However, salt injury to corn has occurred with heavy applications of poultry manure (Weil et al., 1979), and such injury could occur in pastures following injudicious nutrient management.

Potential heavy-metal contaminants originating in inorganic and organic fertilizers include cadmium (Cd), arsenic (As), chromium (Cr),

lead (Pb), mercury (Hg), nickel (Ni), vanadium (V), Cu, and Zn may build up in pastures soils after years of repeated applications (Mordvedt, 1996; Jackson et al., 2003). Of these, Cd is found in phosphate fertilizers and is considered the most important because of its negative human health implications, but estimates indicate that it would take over 1000 yr to reach an intolerable Cd limit (100 mg Cd kg<sup>-1</sup> soil) at typical P rates (20 kg P ha<sup>-1</sup> yr<sup>-1</sup>) (Mordvedt, 1996). Moreover, applications of triple superphosphate or farmyard manure at agronomic rates for more than 60 yr in Missouri had no effect on uptake of Cd by timothy forage, even though slight accumulations of soil Cd had occurred (Mordvedt, 1987).

Animal wastes can contain high concentrations of As, Cu, and Zn owing to their use as biocides or growth promoters, particularly in poultry rations (Jackson et al., 2003). These elements build up in soil after years of manure applications (Kingery et al., 1994), are taken up by forage crops in greater quantities than where manure is not applied (Kingery et al., 1993), and may reach high-enough concentrations in runoff from pastures to cause water-quality problems (Moore et al., 1998). However, we found no reports indicating that soil accumulations of metals owing to manure or fertilizer application resulted in decreased pasture productivity.

Although not a contaminant per se, soil pH is altered by nutrient management in pastures. Ammoniacal fertilizers contribute to surface soil acidity via the nitrification process (e.g., Liebig et al., 2006), which is easily neutralized with agricultural lime (Tisdale et al., 1985). Animal manures contain mostly organic N that is typically easily mineralized to NH<sub>3</sub>/NH<sub>4</sub> N plus antecedent ammoniacal N, yet long-term applications of animal manures increase soil pH due to basic cations, bicarbonates, and organic acids having carboxyl and phenolic hydroxyl groups contained in manure (King et al., 1990; Kingery et al., 1993, 1994; Sharpley et al., 2004).

### Soil Compaction

Soils in permanent pastures and haylands can become compacted over time, owing to animal and vehicle traffic (Tanner and Mamaril, 1959)

that results in retardation of water infiltration, gas exchange, root penetration, and nutrient transformations (Torbert and Wood, 1992; Lee et al., 1996). The CPPE (Table 5.2) for the NRCS Nutrient Management Practice Standard indicates that soil compaction is increased when traffic occurs on moist soils.

The most studied soil physical properties affected by soil management include bulk density, moisture holding capacity, water-stable aggregates, pore space, consistency limits, and strength. But most research involves cropland, particularly under various tillage systems, e.g., conventional tillage versus no-till. However, we found no published studies relating nutrient management to soil physical properties under pasture or haylands in the USA. We also found no published studies regarding amelioration of soil compaction in U.S. pastures or haylands. In Wales, vertical slitting of permanent pasture soils doubled forage production and uptake of N, P, and K (Davies et al., 1989). In New Zealand, mechanical aeration of pastures improved soil physical conditions (Burgess et al., 2000). These studies imply that occasional loosening of soils under permanent pastures will likely improve soil physical conditions, which in turn will increase nutrient uptake and forage production. These types of studies should be conducted on a range of U.S. soils.

### Summary

Much more research on soil properties has been done in row crops, and more studies are needed in pastures and haylands, because the literature is not readily transferable. Most available information on soil properties for pastures and haylands evaluates effects from manure application, likely because of uncertainty associated with lack of accuracy in application rates and the imbalanced manure nutrient ratios in relation to plant nutrient requirements. However, the available studies at international locations indicate that nutrient management can impact soil properties under pastures and haylands.

The U.S. literature suggests that pasture fertilization with chemical fertilizers or animal wastes maintains or moderately improves SOM over the long term, which supports the stated impact promulgated by the NRCS CPPE (Table 5.2). The scientific literature



available studies at international locations indicate that nutrient management can impact soil properties under pastures and haylands.”

Proper nutrient management increases sequestration of soil carbon and improves soil quality.





In general, the practice standard purposes were supported moderately to strongly by the U.S. scientific literature.”

indicates that application of N and P on pastures in excess of plant needs increases the risk of off-site N and P escape. This may result in negative environmental impacts, indicating that proper application rates result in reduced risks of contamination from N, P, and K (Table 5.1). The CPPE for the NRCS Nutrient Management Practice Standard (Table 5.2) indicates that application of excess nutrients will result in increased salts, which may be true with grain crops, but available literature suggests salt buildup in pastures and haylands from long-term fertilizer or manure applications is negligible.

The limited U.S. literature on heavy metal buildup owing to fertilizer or manure application indicates that metals do accumulate in soils where poultry manures are applied long term, but not enough to reduce pasture productivity. Nutrient management affects soil pH, with ammoniacal fertilizers decreasing pH, whereas manure applications raise pH over the long term. The CPPE (Table 5.2) for the NRCS Nutrient Management Practice Standard indicates that soil compaction increases with traffic on moist soils, which is intuitive, but we found no U.S. studies relating nutrient management to soil physical properties in pastures and haylands. More research is needed for a complete understanding of potential relationships.

## CHAPTER SUMMARY

This literature synthesis indicates that proper nutrient management is essential for sustained productivity and environmental compatibility in pasture and hayland systems. We have synthesized the available U.S. literature regarding the purposes of the NRCS Practice Standard 590, which are: 1) budget and supply nutrients for plant production; 2) properly utilize manure or organic by-products as a plant nutrient source; 3) minimize agricultural nonpoint source pollution of surface and groundwater resources; 4) protect air quality by reducing nitrogen emissions (ammonia and NO<sub>x</sub> compounds) and formation of atmospheric particulates; and 5) maintain or improve physical, chemical, and biological condition of the soil. The U.S. scientific literature on nutrient management of pastures and haylands focuses mainly on production-

oriented uses; there is some on environmental issues, but very little on environmental soil properties.

Along with this synthesis, we made subjective assessments of the level of support provided by the U.S. scientific literature for the purposes and criteria that characterize Code 590. In general, the practice standard purposes were supported moderately to strongly by the U.S. scientific literature (Table 5.1). However, this literature synthesis revealed several areas of nutrient management that require further research and development to ensure sustained and environmentally conscious pasture and hayland production in the USA.

With regard to the budgeting and supplying nutrients for plant production purpose of the 590 Practice Standard, much of the additional needed research and development is entwined with the second purpose, i.e., properly use manure or organic by-products as a plant nutrient source. This research and development need is owing to uncertainty regarding phytoavailability of nutrients contained in such nutrient sources. In particular, research is needed regarding 1) development of annual nutrient application rates for production and environmental preservation that account for excreta deposited on grasslands, 2) nutrient spatial distribution from deposited excreta, 3) tools for rapid determination of pools and rates of mineralizable N and P, and those of phytoavailable K in organic nutrient sources, and 4) improvement in manure application equipment to improve uniformity of distribution. Other issues related to budgeting and supplying nutrients for plant production that need further research include: 1) the impact of forage harvest, either by grazing or haying, on nutrient uptake; 2) fertilizer recommendations for intensively managed pastures; and 3) the use of sensors and weather-driven models for adjustment of nutrient application rates.

Simulation models coupled with aforementioned tools for fast determination of pools and rates of mineralizable N and P, and phytoavailable K, in organic nutrient sources could be powerful decision-support tools. Models would assist in transferability of the data among geographic areas and soil types. Collectively, these tools and analytical

procedures would help optimize nutrient management in pasture and hayland systems in the humid areas of the USA.

Similar to the first two purposes of Code 590, uncertainty in minimizing agricultural non-point-source pollution of surface and groundwater resources from pastures and haylands is most prevalent where animal manures and organic by-products are used as nutrient sources. This uncertainty derives from aforementioned reasons, but is also owing to economic reasons, i.e., producers are much less likely to overapply costly commercial fertilizers than manures, especially in areas of intense animal production where finding areas for disposal is a challenge. The literature synthesis indicates that P runoff and NO<sub>3</sub> leaching occur mainly in pasture and hayland systems in regions of concentrated animal production.

It is imperative that BMPs appropriate to a particular CMU (nutrient transport control measures) and decision support tools such as nutrient management planning, the P index and the nitrate-leaching index (nutrient source control measures) be used to retard movement of nutrients out of pasture and hayland systems. A knowledge gap that needs to be bridged is the lack of data on costs, benefits, and cost effectiveness of various BMPs available for retarding nutrient loss from pastures and haylands. With regard to surface movement of P, there is a need to develop a national P index that will accurately predict runoff-P losses over a wide range of conditions. Research is also needed to improve existing models, and to develop new process models that predict nutrient losses from divergent nutrient loadings, soil properties, and climatic conditions.

Synthesis of the limited U.S. scientific literature regarding the Code 590 purpose of protecting air quality by reducing N emissions and formation of atmospheric particulates indicates that gaseous N losses from pastures to the atmosphere are  $\leq 5\%$  of the applied N. The literature suggests that these losses increase with increasing rates of applied N, and that organic N sources result in greater gaseous-N losses than do inorganic-N sources. More research is needed in various regions of the USA regarding pasture and hayland management impacts on N emissions, as most of the work to date has

been done in the southeastern region.

Little research exists on effects of nutrient management in U.S. pastures and haylands on soil properties. Available U.S. scientific literature suggests that pasture and hayland fertilization maintains or moderately improves SOM contents over the long term. The U.S. literature also indicates that over application of N and P to pastures and haylands results in a buildup of these nutrients in the soil that may promote their escape to surface water and groundwater, and escape of N to the atmosphere. Salt buildup was found to be negligible and of no consequence in studies where nutrients were applied to U.S. pastures and haylands. The literature indicates that heavy metals do build up in pasture and hayland soils where animal manures are applied, but no influences from heavy metals on plant productivity were reported. There is some indication that manure applications have a slight liming effect.

No U.S. study was found that evaluated effects of nutrient management on soil physical properties on pasture or hayland. Some of these are known for row crops, but transferability of the effects to perennial pastures and haylands would be difficult. Thus, research on the influence of nutrient management in U.S. pastures and haylands on soil properties is needed to help ensure the sustainability of the soil resource.

In summary, nutrient management is a key component of overall pasture and hayland management. Nutrient management in U.S. pastures and haylands has critical implications for producers, the environment, and society at large. Overall, the production aspects of Code 590 are supported by U.S. research, and in most cases are scientifically sound. However, many aspects of nutrient management were identified that need further scientific support to ensure the future sustainability of our pasture, hayland, water, air, and soil resources. These are pointed out in the text and summarized in Table 5.1.

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A knowledge gap...is the lack of data on...cost effectiveness of various BMPs available for retarding nutrient loss from pastures and haylands.”

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CHAPTER

# 6

## Synthesis and Perspectives

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There was good science to support most purposes and criteria, especially on factors affecting production.”

# Synthesis and Perspectives

C. Jerry Nelson

## INTRODUCTION

This CEAP project aimed to determine the degree that NRCS conservation programs are supported by science and to gain perspectives of the state of science for continuing to address current and emerging problems (Maresch et al., 2008). This report on four selected conservation practice standards for pasture and hayland is part of an overall effort by USDA-NRCS to evaluate a wide range of programs. Earlier CEAP efforts resulted in assessments related to fish and wildlife (Gray et al., 2005; Haufler, 2005, 2007), wetlands (DeSteven and Gramling, 2011), cropland (Schnepf and Cox, 2006, 2007), and rangeland (Briske, 2011). This report covers four major standards for pasture and hayland. Progress reports were made on the overall CEAP (Duriancik et al., 2008) and on the pasture and hayland CEAP (Sanderson et al., 2011).

Each conservation practice standard contains information on why and where the practice is applied and sets forth minimum quality criteria at the national level for implementing the practice. The national standard is more generic, yet addresses national priorities that are relevant. National purposes focus mainly on production as a primary goal while encouraging and leading the landowner to enhance conservation of resources. Each state adapts the practice standard purposes to meet local needs that can be more restrictive than national criteria, but not less. Conservation goals are likely given more emphasis at the state level since they can be more specific, but this was not reviewed.

Evaluation teams assessed a single practice standard in a professional manner. There was good science to support most purposes

and criteria, especially on factors affecting production. In agreement with Tilman et al. (2002) and Maresch et al. (2008), much research is short term and not directly coupled with on-site or off-site measures of environmental and ecosystem services. This is gradually changing since the nature of environmental and ecosystem research requires several years to collect, analyze, evaluate, and publish results. Further, ecosystem-based experiments need to be comprehensive, involve diverse scientists to collect needed data, and long term to reach a reasonable level of ecosystem stability. This chapter considers collectively these and other issues arising from the assessments.

## COMPARATIVE ANALYSIS OF PRACTICE STANDARDS

A matrix was developed to compare purposes of the four standards (Table 6.1). Collectively 12 purposes or major criteria could be grouped, but no standard covered all purposes. This was expected because of differences in management practices used to meet purposes and criteria, and to publication date of the standard. The teams assumed criteria would be further expanded and prioritized at the state level. Further, each national standard is revised about every 5 yr at which time purposes and criteria are updated. Therefore, some disparity may be due partially to publication times for each standard assessed (Code 590 in 2006; Code 528 in 2007; Code 511 in 2008; and Code 512 in 2009; see Appendix I). The detailed CEAP assessments should help focus future revisions.

In general, the first listed purpose for Codes 512, 528, and 511 is on production components, including maintaining plant vigor, desired species composition, and forage



Native grasses and forbs are abundant in natural grasslands of Iowa. NRCS Photo by Lynn Betts.



It is suggested that nutrient management standard (Code 590) be divided into one for crops and one for forage and pastures.”

**TABLE 6.1.** Comparison of key purposes among four practice standards considered in the assessments. Slight wording differences among standards were grouped for this comparison.

Purpose and/or criterion	Code 512 <sup>1</sup>	Code 528 <sup>2</sup>	Code 511 <sup>3</sup>	Code 590 <sup>4</sup>
1. Improve forage yield and quality	X	X	X	X
2. Maintain species, vigor, and regrowth	X	X	X	X
3. Provide feedstock for biofuel	X			
4. Control insects, plant diseases, and weeds	X	X	X	
5. Improve livestock nutrition and health	X	X	X	
6. Optimize nutrient management and uptake			X	X
7. Reduce soil erosion (wind and water)	X	X		X
8. Improve quality of soil and water	X	X		X
9. Improve riparian and watershed function		X		
10. Protect air quality	X			X
11. Enhance carbon sequestration	X	X		
12. Provide fish and wildlife benefits	X	X	X	

<sup>1</sup>Forage and Biomass Planting, <sup>2</sup>Prescribed Grazing, <sup>3</sup>Forage Harvest Management, and <sup>4</sup>Nutrient Management.

quality. The standard for Code 590, nutrient management, covers all crops, so purposes are not as specific for forages and pasturelands, with a focus mainly on nutrient sources, uses, and efficiency. However, criteria within the first purpose of Code 590 can be interpreted to be similar to the other three standards, such as realistic yield goals, but with emphasis on soil management rather than animal responses. Overall, most basic purposes and criteria for production were supported by the literature, at least moderately, for each standard (see Summary Tables 2.11, 3.1, 4.1, and 5.1 in their respective chapters).

### SUGGESTED REVISIONS OF CODES

Code 590 was revised (NRCS, 2012) by reordering the purposes and adding emphasis in criteria for several areas of environmental concern. For example, the 2006 standard used for assessment was based on traditional soil test results that have been replaced by nutrient risk assessments for N and P based on conditions and policies adopted in each state. Minimum application setbacks have been added for sensitive areas such as sinkholes, wellheads, and ditches, and all manure applied needs to be analyzed for N, ammonia

N, total P, total K, and percent solids. In addition, nutrient application rates are defined more quantitatively and use soil erosion risk assessment tools that determine potentials for nutrient and soil loss. Revised Code 590 is more focused and better able to meet national conservation objectives in specific terms, several of which were encouraged by Wood et al. (Chapter 5, this volume).

Despite the revision of Code 590, a disparity continues between acceptable nutrient management practices for perennial pastures and hayland and those for annual grain, oilseed, or fiber crops. It is suggested that nutrient management standard (Code 590) be divided into one for crops and one for forage and pastures. Major reasons include the unique roles of nutrient management of pastures such as recycling of major nutrients, in general, and lack of uniform distribution of urine and feces. More focus will allow the forage standard to address manure and nutrient management related to losses, animal health, and provision of year-round food and habitat for several wildlife species. Most pastures and hay crops are perennials, which offer different timing opportunities for manure applications and managing strategies for improving plant

survival and carbon sequestration (Izaurre et al., 2011). Also, compared with row crops and small grains, perennial forages are often grown on soil sites with lower yield potential and more potential for runoff, situations that need to be considered in the plan.

The 2010 Revised Code 512 includes “biomass” to address a contemporary issue. Codes 511 and 590 should also include biomass in the next title and purposes, and both should add more focus on riparian and watershed function. Splitting row and grain crops from Code 590 to focus on pastures and hayland will give appropriate emphasis to nutrient management for pastures, riparian buffers, grassed waterways, and other sites where perennial plants and their management goals are primary considerations. Likewise, Code 511 should have criteria for erosion control, carbon sequestration, and improvement of soil quality. Perennial forages grown for hay and silage production are renowned for their control of erosion and restoration of eroded land (Hoveland, 2000), which are not emphasized in Code 511 criteria. If not covered, these positive attributes and long-term roles should be pointed out so the topics are not considered an oversight.

### COMPATIBILITY OF CRITERIA AMONG STANDARDS

Scientific evidence was compared for best practices to accomplish purposes and criteria of the selected codes. A cross-cutting evaluation shows most beneficial management practices are consistent for each of the four practice codes, yet there are some inconsistencies in management to achieve the multiple purposes.

#### Ground Cover Is Critical

Adequate ground cover favorably intercepts precipitation and reduces lateral flow to slow water runoff, in both cases reducing erosion. Grazing intensity, while retaining sufficient ground cover, has the major effect on economic return from pastures and is primary to grazing method. Rotational stocking usually provides faster regrowth to reestablish the canopy and more erosion protection than continuous stocking. Achieving ground cover rapidly is a major goal during establishment to allow

the seeded species to compete with weeds and reduce runoff. Yield of alfalfa, but not quality, is increased by leaving short stubble, whereas most grasses and legumes benefit by leaving more stubble, from about 8 cm to 10 cm for upright-growing cool-season grasses, and much taller for upright warm-season grasses.

Early-season harvest of cool-season forage crops can destroy nests of some ground-nesting birds and maim turtles but lead to better nesting success when birds can see predators (Whittingham et al., 2006). Greater diversity in vegetation height occurred with continuous than rotational stocking, whereas mechanical harvest removed the topgrowth more uniformly to the detriment of many wildlife species. Grazing by mixed livestock species was often more economic but reduced variance in ground cover that affected both habitat and food sources for certain birds.

There was less research on effects of ground cover on other ecosystem services, but it was considered beneficial to use a companion crop during establishment, usually a small grain, to reduce environmental risk. The tall companion crop may attract wildlife, only to have some disrupted later by spring harvest for forage during a critical nesting period. Planting into living sods using no-till practices retains ground cover during establishment that reduces environmental risk, but, if not controlled, competition from the sod species increases establishment risk. Also, there may be options to time manure applications based on ground cover, perhaps even when plants are not growing rapidly. Very little research considered roles of ground cover of pasture or hayland to mitigate wind erosion and other air quality factors.

Retaining tall stubble helps reduce soil temperature and plant stress during summer, improve regrowth, conserve sequestered soil carbon during summer, and protect plants over winter. Yet details on stubble height are not well established for the multiple services now expected from pastures and haylands. This suggests an in-depth review of the multiple functions and trade-offs to determine and retain a threshold level of ground cover or basal biomass depending on goals. This should incorporate soil resources,



details on stubble height are not well established for the multiple services now expected from pastures and haylands.”



it is anticipated that more environmental and other ecosystem services will be achieved from multispecies mixtures.”

slope, and landscape position relative to sensitive areas. With pending global change and more severe storms, it behooves scientists and professionals to know the significance and thresholds for guiding more detailed criteria for management of ground cover as part of these standards.

In summary, achieving and maintaining adequate ground cover year-round is foundational for the four practices evaluated, but optimal quantity or height has not been determined for the entire range of grassland products and services. Best management practices for short-term economic return from pasture and hayland have been emphasized. Unfortunately there are few long-term data on how ground cover management affects performance or longevity of the conservation practice, something that should be addressed. In addition, education is needed on how basal ground cover is measured and managed over the long term to achieve multiple objectives of the practice.

### **Establish and Maintain Desired Species**

Each standard addressed this issue based on minimizing encroachment of nonplanted species into monocultures such as alfalfa or maintaining desired mixtures of legumes and grasses. The exception is alfalfa, which is usually managed like a crop, for example, as a pure stand in a crop rotation for a scheduled number of years. With emerging issues about energy costs and environmental conservation there will be continued and even enhanced desire to achieve and maintain appropriate species mixtures, especially legumes, for a longer duration and in rotations (Russelle et al., 2007). But a major limitation is lack of commercial supplies of rhizobia inoculants for native and minor legume species. Private industry is a major player in providing inoculum for major species and should be encouraged to provide inoculum for more species.

Achieving and maintaining a desired species mixture requires management skills based on understanding basic growth principles of preferred plant species and how they interact with companion species. It is difficult to consistently establish desired legume-grass balances via seeding rates or time of seeding

(Chapter 2, this volume), even when using seed treatments, causing need for adaptive management early, usually using defoliation and nutrient management. Further, there are few data on responses of other forbs and minor species. Information on forage values and growth habits of more forbs and grasses is needed including their roles in erosion control and wildlife benefits. Several methods are available for weed control to establish and maintain an alfalfa monoculture, including good herbicides, even glyphosate tolerance, allowing several options. In contrast, adaptive management of grass-legume mixtures depends largely on height and frequency of defoliation and on nutrient management to retain the desired mixture and competitiveness with weeds.

Insect control in alfalfa is well covered, but few research reports exist on insect control, economic thresholds for decision making, or long-term effects on other forage species. Conversely, it is recognized that insects in pasture and hayland are major parts of food chains for wildlife, and some are beneficial as pollinators for legumes and other forbs. Leaf diseases reduce forage quality, and root diseases reduce vigor and persistence; both are usually controlled by seed treatments and cultivar resistance. There are few public plant breeders to develop resistant cultivars, and, except for alfalfa, the private sector places little emphasis on cultivar development (Nelson and Burns, 2006) but does supply quality seed of major species. This leaves a gap in cultivar accessibility, a niche in which USDA-NRCS contributes and could expand its role.

In summary, as purposes shift from primarily production, it is anticipated that more environmental and other ecosystem services will be achieved from multispecies mixtures. This may include more forbs in mixtures and defined management strategies to enhance adaptation to variable soil sites and provide adequate food and protection for wildlife. Plant growth characteristics and compatibility among components in the mixtures need to be understood to provide adequate ground cover year-round. Regular monitoring to note changes and develop options to rebalance mixtures will contribute to experience-based knowledge.

### Improve Livestock Nutrition and Health

For most domestic livestock species there is detailed research on basic principles of management of pastures and haylands to provide high nutritional value and improved livestock performance. Grazing method and nutrient management had less effect on forage quality than on forage production. In contrast, forage quality was affected strongly by harvest frequency and was favored by leaving tall stubble that has major effects on environmental and wildlife outcomes. Harvest and storage losses tend to reduce quality relatively more than yield. First harvest for hay or silage is most subject to rain damage and loss of forage quality with maturity. These quality factors also affect methane production by ruminants and their contribution to greenhouse gases and global change.

Livestock nutrition and health should be part of Code 590 because several animal conditions such as grass tetany, milk fever, nitrate poisoning, mineral imbalances in blood, and bloat (due to proportion of legumes) are related to nutrient management. Also, it is not known what and how nutrient management affects wildlife species. Forb species such as chicory and plantain have been bred for forage use and offer potential through their provision of minerals and trace elements to livestock. Mixed

species of animals offer potentials in production and in providing ecosystem services because species, especially domestic ruminants, tend to select specific components of pastures. Effects of antibiotic and pathogen contaminants in manures on health of livestock, wildlife, and humans are poorly understood.

In summary, broad mechanisms by which protein, fiber and energy support livestock nutrition are well understood; however, other aspects, such as how differences in forage quality affect animal stress and animal health, are not fully known. Mounting public pressure for animal well-being and sustainability of ecosystems will require consideration of this issue.

### Reduce Soil Erosion by Wind and Water

Codes 512, 528, and 590 consider wind and water erosion from different perspectives, yet ground cover is the primary protection. Erosion is not considered directly in Code 511, perhaps because harvested forage is grown on flatter, less erosive soils and is already known to provide protection. This is clearly documented by historical research data and assessment of the Conservation Reserve Program (Hughes et al., 1995). But competition for land is changing due to more biofuel crops (Blanco-Canqui, 2010) and high grain prices displacing pastures

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Grazing method and nutrient management had less effect on forage quality than on forage production.”



Grassed waterway reduces erosion from cultivated field in Kansas. NRCS photo by Jeff Vanuga.



Overgrazed pastures promote soil erosion in Iowa. NRCS photo by Lynn Betts

and hayfields to lower soil quality and sloping land sites. More consideration should be given to ground cover, runoff, and wind erosion on these less-productive areas. This also applies to harvest management of riparian areas and grassed waterways.

Intuitively, risk from wind and especially water erosion is high during establishment of forage species following tillage when there is little ground cover. Although research on methods for erosion control during establishment of forages is very sparse, there is a relative abundance of data on no-till practices for establishing field crops that can be applicable to forages. In addition, some forage plants take more than one growing season to be fully established, so risk is prolonged. Risk of erosion is even higher on sloping soils with low productivity and slow establishment. Runoff

from slopes closer to a water body increases the likelihood of decreased water quality. Once established, the canopy and stubble of hayfields and pastures can be very effective in reducing erosion. Grazing intensity was shown to be a major factor in maintaining adequate cover to minimize erosion risk.

In summary, water and wind erosion remain primary objectives of the agency and need proper attention. The ecosystem costs of lost soil and impaired water need to be quantified. In addition, a small loss of surface soil on lower productivity sites may have greater economic value than the same loss on productive sites. Great strides have been made in control methods including no-till seeding and controlled grazing intensity, and the agency has long experience in developing and implementing soil conservation plans.

Monitoring and cost-benefit data are needed to demonstrate the true value of each conservation practice with time being an integral component. From a public perspective, the question arises: “Is it more cost effective to install and maintain a practice that lasts 20 yr or to install two practices that each last 10 yr?” The answer may be intuitive but is more credible with data.

### Improve Quality of Soil and Water

Soil quality is a comprehensive term that encompasses “fitness for use” or “capacity to function” and is recognized as an important criterion in three of the four standards. It has a series of core components that interact at relative weights to form a quantifiable number (NRCS; see <http://soils.usda.gov/sqi/assessment/assessment.html>) that allows comparative assessments of practices over a range of soils and landscapes. Quality is not easily defined or quantified, and so most measurements include several indicators that are blended (e.g., six in Karlen, 2006). For example, water erosion potential is affected by infiltration rate, soil depth, and physical properties, including bulk density, that indicate water-holding capacity. Infiltration rate and physical properties depend on more detailed components including organic matter.

Similarly, water quality, as mandated by the Clean Water Act, includes several components such as chemicals, microorganisms, soil particles, and general particulate materials. Currently most agricultural research is conducted on plots that represent hayfields or pastures to assess pesticide or nutrient content in runoff or infiltration to ground water. Water quality indicators in experiments reviewed by this CEAP effort included nutrient content, pathogen load, sediment load, turbidity, and responses of fish populations reflecting diversity of interests. This leaves little transferability among experiments to the broader aspects. Components of water to be measured as a quality index should be prioritized and based on intended use, for example, for drinking, health of an ecosystem, or safety for human contact.

In summary, most experiments reviewed were conducted before soil and water quality indices were developed or refined and included only

one or a few measures to evaluate effects on soil quality or water quality. When a new conservation practice is designed and installed the use of water and type of quality assessment should be considered in the management plan. Soil and water quality goals for the site should be defined, appropriate indicators identified, and basic measurements selected for planning and adaptive management of the installation. Standardized sampling and analysis methods would facilitate data transfer and use for models.

### Enhance Sustainability of Agriculture

The public has expanded expectations from agriculture, beyond food, to manage natural resources in a sustainable way that may differ from conservation goals. In some cases, best management practices to conserve soil or water, for example, planting a biofuel crop or installing a riparian buffer, may not be compatible with sustainability of economic production or enhancing diversity of wildlife species. Each practice in place has implied expectations that it will conserve resources for an acceptable time duration and was installed voluntarily. Yet there is growing public concern that farmer decisions depend mainly on markets, policies including incentives, and technical knowledge (Reganold et al., 2011). The goal of a conservation practice within an ecosystem concept should lead to a more sustainable condition that continues, but how will it be funded?

Following a detailed report on alternative agriculture (Natl. Acad. Sci.-Natl. Res. Council, 1989), sustainability of agriculture was addressed as a blend of components of economic return, environmental conservation, production efficiency, and social acceptance. Priorities among components were being questioned, and the public began demanding more output on environmental and social issues, gradually defining and adding more details for each component. For example, the American Society of Agronomy (1989) reached a consensus for the term: “A sustainable agriculture is one that, over the long term, enhances environmental quality and the resource base on which agriculture depends; provides for basic human food and fiber needs; is economically viable; and enhances the quality of life for farmers and society as a whole.”



Each practice in place has implied expectations that it will conserve resources for an acceptable time duration and was installed voluntarily.”



Challenges will be to stay ahead of rapid changes in emphases associated with sustainability and/or ecosystem services.”

The basic concept of sustainability with slightly altered wording was included in the 1990 Farm Bill (US Congress, 1990). Gradually, the terms were refined and components categorized such that sustainability of agriculture was defined, in general, as *Economically Viable*, *Environmentally Sound*, and *Socially Acceptable* (Fig. 6.1). Achieving it required further compartmentalization, definition, and changes.

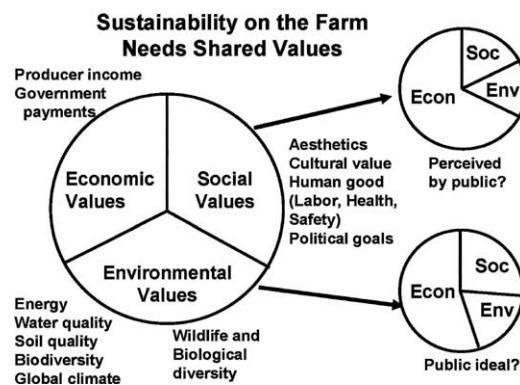
Subsidies have been used to encourage practices for conservation. It is known that when personal incomes increase, the public will pay more for food that is produced in ways that are presumed safe, such as organic, or result in better quality, such as taste (Fig. 6.2), that are not necessarily components of long-term sustainability (Natl. Acad. Sci.- Natl Res. Council. 1989). At high income levels, price premiums for products produced with preservation of wildlife and aesthetics are emerging in Europe (Lemaire et al., 2005) and will become important in the USA. Some, but not all, sustainable production practices can be funded partially or wholly by value-added marketing.

In summary, current approaches have served the agency well as agriculture has developed to meet food needs while conserving soil and water resources. Now a wider range of ecosystem services is expected. Challenges will

be to stay ahead of rapid changes in emphases associated with sustainability and/or ecosystem services. Labels such as “organic,” “natural,” “grass fed,” “healthy,” or “locally grown” entice consumers to pay a higher price to offset reduced yield or higher production costs. These are funded mainly by value-added marketing, do not involve subsidies for other ecosystem services, and differ from conservation practices that have high potential to contribute directly to sustainability.

### Use of Modeling

Each assessment suggested that comprehensive models are invaluable for handling large databases needed for effective planning and documentation of multiple functions from pastures and harvested forages. Modeling can utilize data from existing research, suggest areas for more research, point out areas where adoption of practices may be conflicting with desired outcomes, and incorporate quantifiable ecosystem services and values when that information is known (Carpenter et al., 2009). Information from models will assist in planning conservation practices and determining variables to monitor while the practice is operational. Models could also guide, but probably not direct, adaptive management toward cost-effective ways to restore or maintain the practice (Tonitto et al., 2010).



**FIGURE 6.1.** Sustainability has three major components, but they are arrayed in priority differently by different groups. Social and behavioral scientists are needed to accurately determine the perceptions and value judgments of what sustainability should look like for the general public. Divisions are conceptual because there are no good data for comparison. Adapted from Nelson (2007).

Need for modeling was also highlighted in the Cropland CEAP (Lowrance et al., 2006) and the Rangeland CEAP (Bestelmeyer et al., 2011) with similar issues, yet different approaches based on current efforts and needed results. The Pastureland CEAP suggests a hybridized approach, first, similar to the Rangeland CEAP, to understand mechanisms and interactions of management with purposes for perennials in pastures and haylands at a local level, and, second, similar to the Cropland CEAP, to understand contributions of services when scaled to the landscape level that contains fields of annual crops and other vegetation. The amount of modeling research at the local and landscape levels is more advanced for range and crops than for pastures and hayland. It appears some plant models for rangeland at the local level could be adapted and tested for perennial forage plants. Similarly, landscape models for

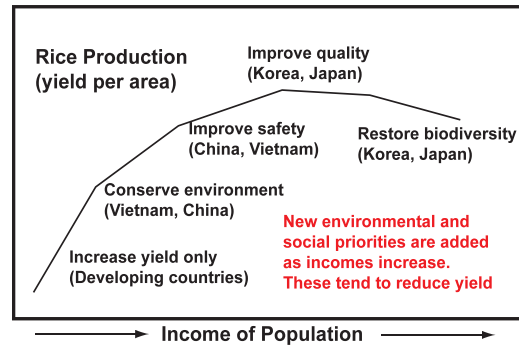
crops could be supplemented with data and models for woodland (Heard et al., 2000) and expanded for inclusion of pastures and haylands. Maps and management units are already defined. Adaptation areas for many forage crops are described (Hannaway et al., 2006).

Some models have been developed to understand roles of pastures and forage crops at the farm level such as DAFOSYM (Rotz et al., 1989) and its major submodels and improvements. Russelle et al. (2007) pointed the direction toward models at larger scales. However, most research evaluated by the CEAP teams was short term and covered some on-site environmental responses, but usually no off-farm responses to the management practices were evaluated. Yet, as public expectations change and solidify, there will be greater need for quantitative data at different levels to capture contributions or impacts of various local management practices beyond the field or farm level. The sheer magnitude of data needed to understand main treatments and interactions requires modern computers and sophisticated models that are becoming available.

In summary, pastures and haylands in the eastern USA are usually associated with annual cropland and/or woodland. Many factors are involved in comprehensive analyses and outcomes are not always consistent across locations for each practice. Models will help understand interactions and give guidance to optimum solutions. Cost-benefit analyses from models will help prioritize programs and generate public support.

### VALUES OF EDUCATION AND MONITORING

Developing and implementing a practice at a given site requires fundamental knowledge supplemented by experience of personnel involved. Local data and agent experience about soil types, topography, species adaptation, and responses to management assist in fine-tuning the practice and predicting outcomes. Interviews of 26 ranchers from a single watershed demonstrated valuable experiences complimented scientific knowledge for site-specific decisions on management and



**FIGURE 6.2.** Relationship between income and rice yield. Country names indicate where on the relationship they fit. Yield increases are lower than potential due to trade-off to provide other desired benefits; for example, rice quality is reduced by high N rates and use of cultivars selected for high yield. Comparable data are not available for pasture and haylands, but the general effect of income on consumer preferences of products is likely similar. Developed by C. Jerry Nelson from several sources including Tilman et al. (2002) and Fischer and Edmeades (2010).

ecological responses (Knapp and Fernandez-Gimenez, 2009). Regular monitoring of practices to note their condition and function adds experience that will be increased further by recommending adaptive management and documenting and evaluating the responses. Outcomes will optimize effectiveness and longevity of the practice.

Currently there is minimal monitoring to determine if the ecosystem goal has been met in terms of its function and longevity. Further, there is no assessment of the long-term costs if the needed conservation practice is not implemented. Evaluation and assessment data are critical in an overall evaluation in terms of what the landowner and the public expects. Periodic monitoring of ecosystem benefits will aid the agency by adding experience, understanding the value of adaptive management, identifying research needs, and determining the collective value of practice lifespan.

In summary, experience is a valuable asset and is needed in local decision making. Monitoring and adaptive management based on combinations of research data and agent experience will help fulfill the



Models will help understand interactions and give guidance to optimum solutions.”



Discussion about pasture management for rotational stocking. NRCS photo

conservation goals, extend the life of the practice, help maintain credibility, and improve cost effectiveness to demonstrate fiscal responsibility.

### POINTING OUT RESEARCH DEFICIENCIES

A major contribution from each assessment team was recognition of critical scientific data required to make quality decisions on planning and implementation of conservation practices, transfer information, and make comparative analyses among experiments. Usually the main focus of research could be augmented by a few basic measures to address multiple objectives and interactions. Critical reviews on basic experimental measures for nonproduction outcomes are needed to identify key data for improving quality and utility of research. A similar recommendation for standardizing measurements arose regarding fish and wildlife benefits from the Wildlife Habitat Incentives Program (WHIP) (Gray et al., 2005). Needs appear to be greatest for measuring management effects associated with nutrient sources, air quality, global change, measures of plant and wildlife diversity, and basic protocols for monitoring practices.

More research needs to be long term, probably for more than 10 yr. For example, in a crop

rotation study on soil quality in Iowa the experiment included rotations of forage and grain crops that extended over 20 yr (Karlen and others, 2006). In a study at three Australian sites (annual rainfall of 554 mm, evenly distributed) accumulation of soil carbon under pastures was not linear; after an initial decrease and lag periods of up to 7 yr, organic carbon increased linearly but had not reached equilibrium in 13 yr (Chan et al., 2011). Nearly all carbon accumulated in the upper 15 cm, with most treatment variation occurring in the upper 5 cm, making sampling depth a major consideration.

A few comprehensive, detailed, and long-term experiments are needed at strategic locations in the USA to form a national framework that incorporates crops and woodland/forest into the farm and landscape effort. The recent development of a Long-Term Agroecosystem Research Network (LTAR) by the USDA-ARS is a step in this direction (Walbridge and Shafer, 2011; <http://www.ars.usda.gov/research/Docs.htm?docid=22480>). The purpose of the network is to address questions related to the condition, trends, and sustainability of agricultural systems and resources on large scales of space and time.

There are continuous changes in science at the national and international levels as new analytical procedures and management technologies become available while major external issues emerge to affect agriculture and public priorities. With modern means of communication and social media the public and agricultural community will redefine priorities continuously and rapidly, often before sufficient research has been conducted to evaluate the responses and interactions. Without research as a guide, the time disconnect will require compromises and decisions by professionals designing conservation practices based mainly on intuition from component studies and early personal experiences that can be questioned.

In summary, research funding and management need to be long term and place more emphasis on broad aspects of pasture and hayland research. Both public and private funding will be needed. International connections will assist with methodologies and data acquisition

but require refinement for use in specific and variable sites. Strong partnerships among state universities and federal agencies will add comprehensiveness and help justify long-term investments. Understanding the methods and translating interdisciplinary research into useful education programs will be essential.

### FUTURE PARAMETERS FOR CONSERVATION PRACTICES

There are a myriad of emerging issues that will need attention of NRCS and the new generation of Conservation Practice Standards. Some are already well developed. Most require the agriculture community to be involved with a broad range of disciplines and new partners. Each has its own timeline, level of public support, relative importance, and uniqueness that will require it be dealt with in its own way. International relations on trade (for example, mad cow disease or hay marketing), role of genetically modified plants, and residue effects from pharmaceuticals, probiotics, and *E. coli* could be on an exhaustive list.

#### *Integrate Sustainability and Resilience.*

Sustainability has been an issue for a long time beginning with public interest in low-input sustainable agriculture (LISA), but the scientific community believed low input meant “organic,” which was too restrictive, and argued that agriculture could be sustainable with high inputs. There was some thought about “multifunctional,” a term used in Europe and Asia, but functions were broad in scope and not clearly defined. Finally, the US agricultural community agreed on *sustainable agriculture*, which included three general components: (1) economically viable, (2) environmentally sound, and (3) socially acceptable (Fig. 6.1). The definition was used mainly for land resources and applied primarily at the farm level, although many thought it should be landscape or watershed based (Gold, 1999, revised 2007).

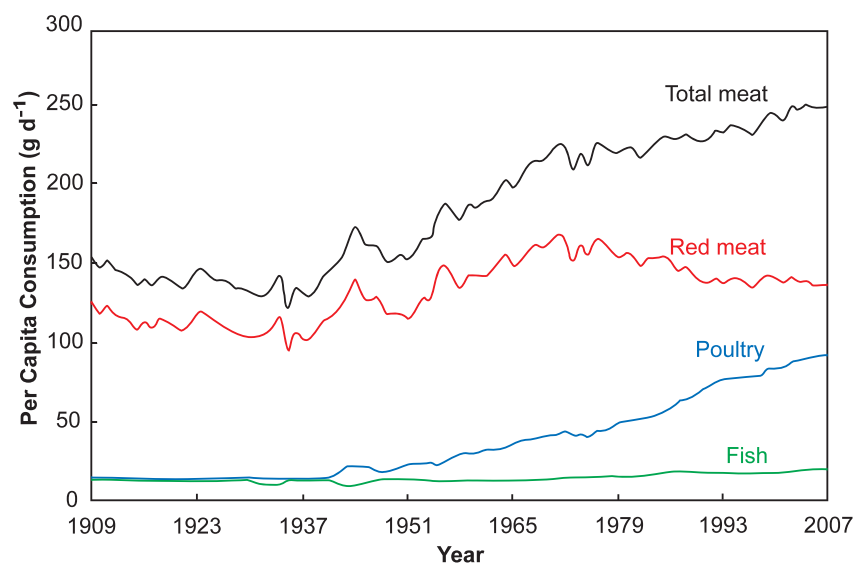
Economic production could be evaluated, but mechanisms for measuring and valuing the other two components are not clear. Public perception is farmers place greatest emphasis on economic production with little consideration of environmental and social effects during long-range planning and daily decision making (Fig.

6.1). As society develops and personal income increases there is public demand for more and better contributors to sustainability and the human condition (Nelson, 2007). Similar to developing countries, the primary focus of low-income consumers is on increased supply of affordable food (Fig 6.2). As incomes rise, more emphasis is placed on environmental issues, which often results in reduced rate of yield increase. As incomes continue to increase, the public demands food safety, followed by food quality and finally by increased biodiversity of plants and animals. Each service reduces the rate of production gain due to “fitness penalties” and altered management that is needed to achieve goals.

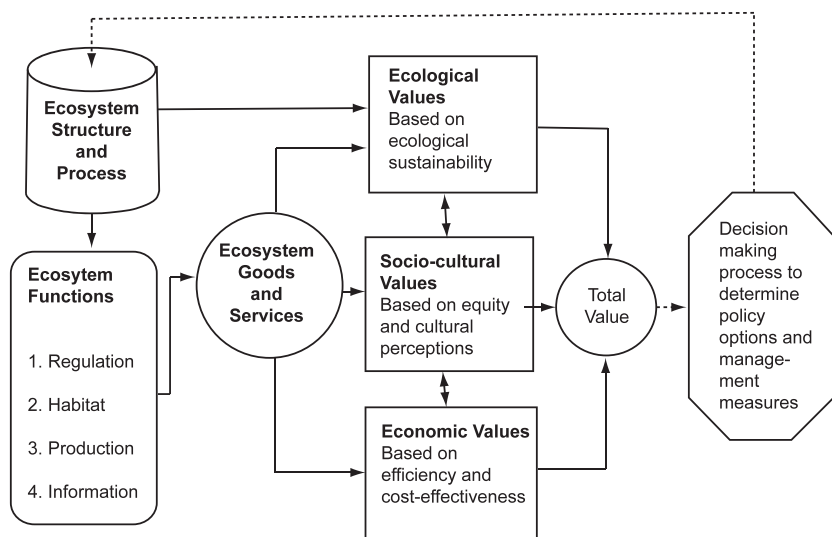
In the USA and other developed countries, current public pressure is on food safety, such as the *E. coli* challenges, and food quality, which is associated with freshness and taste. Emphasis is on eating *healthy*, which includes purchase of locally grown food that is fresh and often organic. Following the lead of Europe and developed countries in Asia, more emphasis on wildlife and other forms of biodiversity are expected to be provided by agriculture. High-income consumers will pay more for organic food that is pesticide free and assumed to be healthy. The trend for healthy food has been accompanied by dietary shift to more vegetables and fruits as well as fewer red meats



As society develops and personal income increases there is public demand for more and better contributors to sustainability and the human condition”



**FIGURE 6.3.** Consumption of meat and meat products is increasing, but that of red meat is decreasing. Reasons include health consciousness and relative cost. Data are from USDA-ERS and Daniel et al. (2011).



**FIGURE 6.4.** Proposed flow chart of management decisions (right) and the resulting changes in ecosystem function and resulting ecosystem goods and services as they relate to sustainability. Adapted from de Groot et al. (2002).

and other foods that have high fat content (Fig. 6.3). Meat consumption per capita in the USA continues to gradually increase, mainly due to preferences for poultry, while beef consumption is decreasing (Daniel et al., 2011), which has effects on pasture and hayland. Pork consumption has remained relatively steady.

Current emphasis is now adding *resilience*, the ability to produce consistently every year (Allen and Brown, 2006; Hoffmaister, 2009; Woolley and Douthwaite, 2011). This is partially in response to more variable weather events associated with global climate change and to international and national priorities on food security, especially stable grain prices. Cultivars and crop management systems will need to *consistently* provide the quantity and quality of food in a sustainable manner along with increased efforts to increase provision of other goods and services. Potential drastic events involve weather variables, disease, or insect outbreaks against vulnerable cultivars, and even calamities such as wars and terrorism (Rosa et al., 2012). These drastic changes are often abrupt and localized.

In summary, it will be difficult for new cultivars to maintain consistent yields while overcoming the fitness penalty needed for resilience to stresses. Using defensive measures in crop management to gain

resilience will likely result in short-term yield reduction as more conservative practices are used. To date, there has been little research on how increasing resilience of agriculture will fit into the larger picture of environmental stewardship in a socially acceptable way. Regardless, the older, three-component model for sustainability is being replaced by an emerging concept that requires high output of sustainable production with resilience while providing even more environmental and social services.

**Technologies to Address Ecosystem Services.** Based on needs for addressing ecological and social issues the concept of *ecosystem services* emerged as an ecological approach to describe desired outputs from natural ecosystems. Several attempts to relate sustainability and ecosystem services were attempted. For example, one detailed conceptual framework and typology proposed 24 specific functions that could be allocated among four services to describe, classify, and value ecosystem goods and services that link with sustainability (Fig. 6.4). Later these approaches were coalesced by the Millennium Ecosystem Assessment project (Carpenter et al., 2009) into a set of four major outputs or services from natural (production remaining on-site) or managed (production moving off-site) ecosystems. These include the following:

- Supporting services (including primary production, nutrient cycling, and soil formation)
- Provisioning services (including food, fresh water, wood, fiber, and fuel)
- Regulating services (including regulation of climate, quantity and quality of water, and diseases)
- Cultural services (including aesthetics, spiritual issues, education and recreation).

Supporting and regulating services are considered fundamental for natural processes and set parameters for human intervention effects on provisional and cultural services. Production factors of agriculture are located mainly in provisioning services. The shift in classification from three services for sustainable agriculture to four ecosystem services makes it more difficult for the agriculturalist to assign priorities and use the correct measures. It

would be impossible to measure all services in one experiment, so researchers need to identify key indicators for each component. This is similar in concept to measures of soil quality or water quality and will eventually lead to models that are capable of integrating many variables.

In summary, public agencies such as NRCS should evaluate and consider conservation standards that incorporate sustainability, resilience, and delivery of ecosystem services. Alternatively the decision may be to remain within the realms of conservation and make connections and cooperation with agencies that focus on other services. Regardless, the issue should be addressed and be reflected in the next generation of conservation standards.

### *Determining Values of Ecosystem Services.*

Economic returns for forages or pastures depend on input costs and output values in monetary terms, but currently there is no good way to value issues such as water, air or soil quality, an aesthetic view or improved wildlife biodiversity. Early attempts to evaluate cost benefits for forage management practices have used market pricing (e.g., Caddel et al., 1995) or nonmarket estimates to evaluate program outcomes (e.g., Hughes et al., 1995, for CRP). But these methods are not comprehensive over all services. For example, it is known that delay of first harvest of hay and silage crops will improve nesting success (Chapter 4, this volume). Can this be interpreted to mean that the calculated dollar loss in quality and yield of forage can be assumed to be the true value of the wildlife conserved?

Ecological economists are developing methods to evaluate ecosystem services for decision making. One or more evaluation methods may be needed to gain information that is compatible for comparisons and models, each depending on inputs from a comprehensive database (Villa et al., 2002). Current databases are inadequate except for a few locations, one being the San Pedro Riparian National Conservation Area in California. Based on that comprehensive database for a small natural stream, scientists modeled changes in vegetation, water flow, and bird abundance after grazing was stopped (Brookshire et al., 2010). They are now determining economic values for services based on *choice modeling*,

i.e., preferences based on public surveys, and *contingent evaluation*, i.e., public preferences based on statements of willingness and amounts they would pay for each service.

Values of ecosystem services at the national level have been considered “well-being” of the populace and could be “measured” from the gross domestic product (GDP); that is, as the GDP increases it is assumed well-being also increases. To evaluate this aspect relative to a range of sites, including the Chesapeake Bay, the Genuine Progress Indicator (GPI) or a derivative called the Index of Sustainable Economic Welfare was based on multiple indicators including parts of the GDP that directly measure benefits to people. The index then corrects the number by adding or subtracting economic, environmental, and social factors, all expressed in monetary values (McGuire et al., 2012). The indices have been tested in more than 20 countries and document that GDP is not a good measure of improved welfare or values of ecosystem services. This is consistent with Fig. 6.2, which shows factors are prioritized and respond independently.

In summary, there are many ways to participate in the emerging “biodiversity science” (Larigauderie and Mooney, 2010). The NRCS could contribute to integration of conservation practices as a positive human intervention that adds valued ecosystem services. The long-term support for biodiversity science will also compete with other agencies for public funding, especially for long-term programs of environmental or social value. Models based on interagency cooperation may be the desirable outcome.

*Climate Change.* The gradual increases in atmospheric concentrations of CO<sub>2</sub> and methane are predicted to increase average air temperature, lengthen the growing season, accelerate phenological development, lead to variable precipitation and more violent storms, and increase pest problems (Izaurrealde et al., 2011). Higher CO<sub>2</sub> concentration will increase photosynthesis and growth of most C<sub>3</sub> species to partially offset the reduction due to higher temperatures. Pastures and haylands will be expected to contribute to mitigation by using less fossil fuel in producing and using these resources. Minimum tillage for establishment,



Ecological economists are developing methods to evaluate ecosystem services for decision making.”



water is rapidly becoming a scarce natural resource and will demand more efficient use from agriculture.”

legumes in rotations for nitrogen fixation, and grazing to harvest the forage, perhaps even to time of animal harvest, will help. Manure management on pastures will be a priority for efficient use, and good nutrition of ruminants will be emphasized to reduce methane production.

These practices will save fuel costs, help sequester and retain carbon in the soil, and reduce labor costs. Adding forages as winter cover in crop rotations will reduce soil loss, improve water quality, and provide wildlife habitat. Most of these technologies have had partial research to form the foundation. Biotic and abiotic stresses on plants will increase because temperatures are expected to be higher (Howden et al., 2007). Higher temperatures may increase virulence of pathogens and activity of insect pests that reduce production and quality of pasture and hayland species. Activity of pollinators may be decreased to alter seed costs and food supplies for wildlife. In addition, increased year-to-year variability will require emphasis on resilience as well as sustainability as conditions change. If change is relatively slow, plant and animal communities can adjust naturally. In summary, there are many unknowns regarding the magnitude and effects of climate change.

#### *Water Quality and Water Supplies.*

Agriculture accounts for nearly 80% of the total water use in the USA and is being strongly encouraged to reduce amounts and increase use efficiency (Howden et al., 2007; Maresch et al., 2008). Growth of cities and communities will increase demand for high-quality, dependable supplies that are free of sediment, pharmaceuticals, microorganisms, and other contaminants, many of which come from agriculture. Simultaneously, predicted climate change will place even more pressure on soil conservation, general water supplies, water quality, and the public quest to reduce flooding and restore wetlands. Water use will be an issue as the Ogallala aquifer and other sources are reduced, leading to reversion of some land to grasslands for animal or biofuel production.

The roles and management of forages in waterways, riparian areas, and other sensitive landscape positions will increase, as will watershed “cooperatives” that allow rural and

urban citizens to address water quality and other problems at landscape levels instead of the field or farm level.

Restoring forages and pastures into rotations and cropping systems may best mitigate these changes (Russelle et al., 2007; Izaurrealde et al., 2011). Regardless of the degree of climate change, the nation must be prepared with technology and be flexible in its use to effectively manage available water resources.

In summary, water is rapidly becoming a scarce natural resource and will demand more efficient use from agriculture. Solutions will likely depend on public support, use of community-based efforts, and integration of several disciplines for research and education while strengthening the interface with decision makers. This should be assisted by better use of weather forecasting and models to reduce risk.

*Energy Issues and Biofuels.* There is strong national interest to develop biofuels and mitigate global climate change without competing for use of food and feed crops such as corn or soybean (Sanderson and Adler, 2008). Perennial grasses are potential sources for direct combustion or biological conversion of cellulose for useful forms. Less fossil fuel energy is needed to maintain perennial crops, making them more efficient based on input/output energy balances. In addition, they conserve soil year round, improve soil hydraulic properties, and can sequester large amounts of CO<sub>2</sub> equivalents into soil organic matter (Blanco-Canqui, 2010). Wildlife benefits depend on when the crop is harvested mechanically and may be best when harvesting leaves a mosaic of harvested and nonharvested patches (Fargione et al., 2009).

Bulky energy crops will be grown near conversion facilities to conserve transport energy, but it is unclear in what locations these crops will have a comparative advantage. Some biofuel grasses take 2 yr or more to become established, so they do not fit short-term rotations. Basic principles for growth and composition of energy crops are often similar to forage grasses, so there will be reciprocal benefits from biofuel research to forage-livestock situations. Fields used for biofuel crops may be very suitable and/or preferred

sites for manure applications. Significant land use change due to converting grasslands to bioenergy production to meet national biofuels targets and favorable economics may pressure land used currently for hay, silage, and pasture.

In summary, need for mechanical harvest of biofuel crops favors their use on flatter soil sites, further forcing forage and pastureland production onto more marginal lands. At the time of this writing, however, crop commodity prices are also high, causing further economic pressure to convert pasture and haylands to annual crop production.

### *Changing Food Consumption Patterns.*

Obesity of US citizens is increasing, especially for children and youth, leading to policies and expanded educational attempts to mitigate this trend. Fruits and vegetables, low-fat meats and milk, and substitutes for some dairy products are being encouraged. There is movement toward more “natural” and organically produced food, including meat and milk, which rely heavily on forage and pasture use. In addition, growing demand for locally produced foods for freshness and quality will require more forage and pastureland to provide diversity of animal products from farms that market directly to urban populations.

Consumption of beef and milk, which depend largely on pastures, hay, and silage, is decreasing. Conversely, grass-finished beef is considered to be healthier, and demand for “healthy beef” may require extended time on pasture and stored forage before animals are harvested or supplemented with grains. Additional time on pasture will affect manure management and reduce odors often associated with confined livestock. Grass-fed beef and pasture-based milk production will likely continue to grow in demand based on animal rights, healthiness, and being more natural. Thus, reduced consumption of beef and milk may actually be associated with an increase in area used for pasture and hayland.

## CONCLUSIONS

The USDA-NRCS is entering a new era with CEAP, a rich and unparalleled assessment of the science foundation for its products and services that offers credibility for the present and insight



Monitoring water quality in a tributary stream in Iowa. NRCS photo by Lynn Betts

for the future. The new paradigm indicates that the science base for implementing practices is only part of the long term because the audience and public expectations for what agriculture can and should provide have expanded and continue to expand. To date, research has usually focused on managing to optimize economic return to the landowner with some measurements of environmental, social, or other ecosystem factors. Very rarely have there been attempts to perform economic analyses of the responses; in fact, it is very difficult to



The collective worth of an installed practice will be well beyond the subsidy the landowner receives.”

determine the value, intrinsic or actual, of nearly all environmental or ecosystem services. This is complicated further by mounting public pressures for provision of even more ecosystem services from agriculture.

Procedures are needed for monitoring implemented practices and providing effective educational programs about key outcomes expected and how to utilize adaptive management. Educational and planning efforts at the local level involving communities, and individuals could set realistic goals and estimate values for the blend of ecosystem services expected at a larger scale. These values will likely differ from location to location. Then goals of each landowner can be quantifiably used to estimate that contribution to the whole.

The collective worth of an installed practice will be well beyond the subsidy the landowner receives, and the return value of services needs to be communicated to policy makers and the public. This new agenda will require interdisciplinary research and education efforts by teams, including soil scientists, agronomists, animal scientists, ecologists, economists, and sociologists.

Throughout, the CEAP project has been working on a moving target. The CEAP effort is based on assessment of previous research for support of the current practice standards. Fortunately the review teams were charged to consider broader aspects, recognizing the change in public expectations will be critical for the next generation of practices. The futuristic approach also is helpful in planning to meet shortfalls in the amount, style, and comprehensiveness of research. Clearly a major issue is “how does the agricultural community move forward at an accelerated pace to meet the changing expectations in a credible manner?”

In summary, most purposes and criteria are supported by published research, but the level of support differs among criteria. In several cases there is insufficient research to be fully confident of support. In others, research is sound and supportive but limited in geographic area, so transferability to other environments and landscapes is limited. Clearly the landowner goals and compliance will be key to continued use of volunteer programs, yet

desires of the public and credibility of programs need to be considered in how landowners manage the practice for effectiveness and longevity. Above all, the agency and the scientific community need to anticipate new challenges and be prepared to address emerging issues in a manner that is science based and socially acceptable. Public confidence that the system is functioning to conserve resources and provide diverse services in a credible way must always remain a primary goal.

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## NATURAL RESOURCES CONSERVATION SERVICE CONSERVATION PRACTICE STANDARD

### FORAGE AND BIOMASS PLANTING

(Ac.)

CODE 512

#### DEFINITION

Establishing adapted and/or compatible species, varieties, or cultivars of herbaceous species suitable for pasture, hay, or biomass production.

#### PURPOSE

- Improve or maintain livestock nutrition and/or health.
- Provide or increase forage supply during periods of low forage production.
- Reduce soil erosion.
- Improve soil and water quality.
- Produce feedstock for biofuel or energy production

#### CONDITIONS WHERE PRACTICE APPLIES

This practice applies all lands suitable to the establishment of annual, biennial or perennial species for forage or biomass production. This practice does not apply to the establishment of annually planted and harvested food, fiber, or oilseed crops.

#### CRITERIA

##### General Criteria Applicable to All Purposes

Select plant species and their cultivars based on:

- Climatic conditions, such as annual precipitation and its distribution, growing season length, temperature extremes and the USDA Plant Hardiness Zone.

- Soil condition and landscape position attributes such as; pH, available water holding capacity, aspect, slope, drainage class, fertility level, salinity, depth, flooding and ponding, and levels of phytotoxic elements that may be present.
- Resistance to disease and insects common to the site or location.

Follow recommendations for planting rates, methods and dates obtained from the plant materials program, land grant and research institutions, extension agencies, or agency field trials.

Seeding rates will be calculated on a pure live seed (PLS) basis.

Plant at a depth appropriate for the seed size or plant material, while assuring uniform contact with soil.

Prepare the site to provide a medium that does not restrict plant emergence.

Plant when soil moisture is adequate for germination and establishment.

All seed and planting materials will meet state quality standards.

Do not plant federal, state, or local noxious species.

Apply all plant nutrients and/or soil amendments for establishment purposes according to a current soil test. Application rates, methods and dates are obtained from the plant materials program, land grant and research institutions, extension agencies, or agency field trials.

When planting legumes, use pre-inoculated seed or inoculate with the proper viable strain of Rhizobia immediately before planting.

Conservation practice standards are reviewed periodically, and updated if needed. To obtain the current version of this standard, contact the Natural Resources Conservation Service.

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Exclude livestock until the plants are well established.

Select forage species based on the intended use, level of management, realistic yield estimates, maturity stage, and compatibility with other species. Verify plant adaptation to the area prior to planting.

**Additional Criteria for Improving or Maintaining Livestock Nutrition and/or Health**

Use forage species that will meet the desired level of nutrition (quantity and quality) for the kind and class of the livestock to be fed.

Forage species planted as mixtures will exhibit similar palatability to avoid selective grazing.

**Additional Criteria for Providing or Increasing Forage Supply During Periods of Low Forage Production**

Select plants that will help meet livestock forage demand during times that normal farm/ranch forage production are not adequate.

**Additional Criteria for Reducing Erosion and Improving Water Quality.**

Ground cover and root mass need to be sufficient to protect the soil from wind and water erosion.

**Produce Feedstocks For Biofuel or Energy Production**

Select plants that provide adequate kinds and amount of plant materials needed.

**CONSIDERATIONS**

In areas where animals congregate consider establishing persistent species that can tolerate close grazing and trampling.

Where wildlife and pollinator concerns exist, consider plant selection by using an approved habitat evaluation procedure.

Where air quality concerns exist consider using site preparation and planting techniques

that will minimize airborne particulate matter generation and transport.

Where carbon sequestration is a goal select deep rooted perennial species that will increase underground carbon storage.

During and upon stand establishment planning and application of the following conservation practices should be considered as applicable; Forage and Biomass Harvest (511), Herbaceous Weed Control (315), Nutrient Management (590), and Prescribed Grazing (528).

**PLANS AND SPECIFICATIONS**

Prepare plans and specifications for the establishment planting for each site or management unit according to the Criteria, Considerations, and Operations and Maintenance described in this standard. Record them on a site specific job sheet or in the narrative of a conservation plan.

The following elements will be addressed in the plan to meet the intended purpose:

- Site Preparation
- Fertilizer Application (if applicable)
- Seedbed/Planting Bed Preparation
- Methods of Seeding/Planting
- Time of Seeding/Planting
- Selection of Species
- Type of legume inoculant used (if applicable)
- Seed/Plant Source
- Seed Analysis
- Rates of Seeding/Planting
- Supplemental Water for Plant Establishment (if applicable)
- Protection of Plantings (if applicable)

**OPERATION AND MAINTENANCE**

Inspect and calibrate equipment prior to use. Continually monitor during planting to insure

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proper rate, distribution and depth of planting material is maintained.

Monitor new plantings for water stress. Depending on the severity of drought, water stress may require reducing weeds, early harvest of any companion crops, irrigating when possible, or replanting failed stands.

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## NATURAL RESOURCES CONSERVATION SERVICE CONSERVATION PRACTICE STANDARD

### PRESCRIBED GRAZING

(Ac.)

CODE 528

#### DEFINITION

Managing the harvest of vegetation with grazing and/or browsing animals.

#### PURPOSE

This practice may be applied as a part of conservation management system to achieve one or more of the following:

- Improve or maintain desired species composition and vigor of plant communities.
- Improve or maintain quantity and quality of forage for grazing and browsing animals' health and productivity.
- Improve or maintain surface and/or subsurface water quality and quantity.
- Improve or maintain riparian and watershed function.
- Reduce accelerated soil erosion, and maintain or improve soil condition.
- Improve or maintain the quantity and quality of food and/or cover available for wildlife.
- Manage fine fuel loads to achieve desired conditions.

#### CONDITIONS WHERE PRACTICE APPLIES

This practice applies to all lands where grazing and/or browsing animals are managed.

#### CRITERIA

##### General Criteria Applicable to All Purposes

Removal of herbage will be in accordance with

site production limitations, rate of plant growth the physiological needs of forage plants and the nutritional needs of the animals.

Adequate quantity and quality drinking water will be supplied at all times during period of occupancy.

Adjust intensity, frequency, timing and duration of grazing and/or browsing to meet the desired objectives for the plant communities and the associated resources, including the grazing and/or browsing animal.

Manage kind of animal, animal number, grazing distribution, length of grazing and/or browsing periods and timing of use to provide grazed plants sufficient recovery time to meet planned objectives. The recovery period of non-grazing can be provided for the entire year or during the growing season of key plants. Deferment (non-grazing period less than one year) and/or rest (non-grazing period equal or greater than one year) will be planned for critical periods of plant needs.

Provide deferment or rest from grazing or browsing to ensure the success of prescribed fire, brush management, seeding or other conservation practices that cause stress or damage to key plants.

Manage grazing and/or browsing animals to maintain adequate vegetative cover on sensitive areas (i.e. riparian, wetland, habitats of concern, karst areas).

Manage livestock movements based on rate of plant growth, available forage, and allowable utilization target.

Develop contingency plans to deal with expected episodic disturbance events e.g.

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insect infestation, drought, wildfire, etc.

**Additional Criteria to Improve or Maintain the Health and Vigor of Plant Communities.**

Duration and intensity of grazing and/or browsing will be based on desired plant health and expected productivity of key forage species to meet management objectives.

Plan periodic deferment from grazing and/or browsing to maintain or restore the desired plant community following episodic events, such as wildfire or severe drought.

Where appropriate, soil test periodically for nutrient status and soil reaction and apply fertilizer and/or soil amendments according to soil test to improve or maintain plant vigor.

**Additional Criteria to Improve or Maintain Quantity and Quality of Forage for Animal Health and Productivity**

Plan grazing and/or browsing to match forage quantity and quality goals of the producer within the capability of the resource to respond to management.

Enhance diversity of rangeland and pasture plants to optimize delivery of nutrients to the animals by planning intensity, frequency, timing and duration of grazing and/or browsing.

Plan intensity, frequency, timing and duration of grazing and/or browsing reduce animal stress and mortality from toxic and poisonous plants.

Supplemental feed and/or minerals will be balanced with the forage consumption to meet the desired nutritional level for the kind and class of grazing and/or browsing livestock.

Dietary needs of livestock will be based on the National Research Council's Nutrient Requirements of Domestic Animals or similar scientific sources with appropriate adjustments made for increased energy demand required by browsing or grazing animals foraging for food including travel to and from pasture site.

Biosecurity safeguards will be in place to prevent the spread of disease between on-farm or ranch classes of livestock and between livestock farm or ranch units.

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Shelter in the form of windbreaks, sheds, shade structures, and other protective features will be used where conditions warrant to protect livestock from severe weather, intense heat/humidity, and predators.

**Additional Criteria to Improve or Maintain Surface and/or Subsurface Water Quality and Quantity.**

Minimize concentrated livestock areas to enhance nutrient distribution and improve or maintain ground cover.

Plan intensity, frequency, timing and duration of grazing and/or browsing to:

Minimize deposition or flow of animal wastes into water bodies,

Minimize animal impacts on stream bank or shoreline stability.

Provide adequate ground cover and plant density to maintain or improve infiltration capacity and reduce runoff.

Provide adequate ground cover and plant density to maintain or improve filtering capacity of the vegetation.

**Additional Criteria to Improve or Maintain Riparian and Watershed Function.**

Minimize concentrated livestock areas to enhance nutrient distribution and improve or maintain ground cover and riparian/floodplain plant community structure and functions.

Plan intensity, frequency, timing and duration of grazing and/or browsing to:

Provide adequate ground cover and plant density to maintain or improve infiltration capacity and reduce runoff.

Provide adequate ground cover and plant density to maintain or improve filtering capacity of the vegetation.

Maintain adequate riparian community structure and function to sustain associated riparian, wetland, floodplain and stream species.

**Additional Criteria to Reduce Soil Erosion and Maintain Soil Condition**

Minimize concentrated livestock areas, trailing, and trampling to reduce soil compaction, excess runoff and erosion.

Plan intensity, frequency, timing and duration of grazing and/or browsing to provide adequate ground cover, litter and canopy to maintain or improve infiltration and soil condition.

**Additional Criteria to Improve or Maintain Food and/or Cover for Fish and Wildlife Species of Concern**

Identify species of concern in the objectives of the prescribed grazing plan.

Plan intensity, frequency, timing and duration of grazing and/or browsing to provide for the development and maintenance of the plant structure, density and diversity needed for the desired fish and wildlife species of concern.

**Additional Criteria for Management of Fine Fuel Load**

Plan intensity, frequency, timing and duration of grazing and/or browsing to reduce hazardous fuel loads.

Plan intensity, frequency, timing and duration of grazing and/or browsing to manage fuel continuity, load and other conditions to facilitate prescribed burns.

**CONSIDERATIONS**

Protect soil, water, air, plant and animal resources when locating livestock feeding, supplementing, handling and watering facilities.

Livestock feeding, handling, and watering facilities will be designed and installed in a manner to improve and/or maintain animal distribution. These facilities will also be designed and installed to minimize stress, the spread of disease, parasites, contact with harmful organisms and toxic plants.

Utilization or stubble height target levels are tools that can be used in conjunction with monitoring to help ensure that resource conservation and producer objectives are met.

Where practical and beneficial, start the grazing sequence in a different management unit each growing season.

When weeds are a significant problem prescribed grazing and/or browsing should be implemented in conjunction with other pest management practices to promote plant community resistance to invasive species and protect desired plant communities.

Prescribed grazing should consider the needs of other enterprises utilizing the same land, such as wildlife and recreational uses.

Consider improving carbon sequestration in biomass and soils through management of grazing and/or browsing to produce the desired results.

If nutrients are being applied, Nutrient Management (590) will be applied.

**PLANS AND SPECIFICATIONS**

The prescribed grazing plan shall conform to all applicable federal, state and local laws. Seek measures to avoid adverse affects to endangered, threatened, and candidate species and their habitats.

Prepare a prescribed grazing plan for all planned management units where grazing and/or browsing will occur according to state standards and specifications.

Prescribed Grazing Plan will include:

- Goals and Objectives clearly stated.
- Resource Inventory that identifies:
  - existing resource conditions and concerns
  - ecological site or forage suitability group
  - identifies opportunities to enhance resource conditions
  - location and condition of structural improvements such as fences, water developments, etc, including seasonal availability and quality of watering sites.
- Forage Inventory of the expected forage quality, quantity and species in each management unit(s).

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- Forage-Animal Balance developed for the grazing plan, which ensures forage produced or available meets forage demand of livestock and/or wildlife.
- Grazing Plan developed for livestock that identifies periods of grazing and/or browsing, deferment, rest, and other treatment activities for each management unit.
- Contingency plan developed that details potential problems (i.e., severe drought, flooding, insects) and serves as a guide for adjusting the grazing prescription to ensure resource management and economic feasibility without resource degradation.
- Monitoring plan developed with appropriate records to assess in determining whether the grazing strategy is resulting in a positive or upward trend and is meeting objectives. Identify the key areas and key plants that the manager should evaluate in making grazing management decisions.

#### OPERATION AND MAINTENANCE

**Operation.** Prescribed Grazing will be applied on a continuing basis throughout the occupation period of all planned grazing units.

Adjustments will be made as needed to ensure that the goals and objectives of the prescribed grazing strategy are met.

**Maintenance.** Monitoring data and grazing records will be used on a regular basis within the prescribed grazing plan to insure that objectives are being met, or to make necessary changes in the prescribed grazing plan to meet objectives.

All facilitating and accelerating practices (e.g. Fence (382), Pest Management (595), Brush

Management (314), Pasture Planting (512) (etc.) that are needed to effect adequate grazing and/or browsing distribution as planned by this practice standard will be maintained in good working order and are being operated as intended.

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## NATURAL RESOURCES CONSERVATION SERVICE CONSERVATION PRACTICE STANDARD

### FORAGE HARVEST MANAGEMENT

(Ac.)

CODE 511

#### DEFINITION

The timely cutting and removal of forages from the field as hay, green-chop or ensilage.

#### PURPOSE

- Optimize yield and quality of forage at the desired levels
- Promote vigorous plant re-growth
- Manage for the desired species composition
- Use forage plant biomass as a soil nutrient uptake tool
- Control insects, diseases and weeds
- Maintain and/or improve wildlife habitat

#### CONDITIONS WHERE PRACTICE APPLIES

This practice applies to all land uses where machine harvested forage crops are grown.

#### CRITERIA

##### General Criteria Applicable to All Purposes

Forage will be harvested at a frequency and height that optimizes the desired forage stand, plant community, and stand life. Follow State Cooperative Extension Service (CES) recommendations for forage harvest based on stage of maturity, moisture content, length of cut, stubble height and harvest interval. The following criteria must be met:

**Stage of Maturity.** Harvest forage at the stage of maturity that provides the desired quality and quantity without compromising plant vigor and stand longevity.

**Moisture Content.** Harvest silage/haylage crops within the optimum moisture range for the type of storage method(s) or structure(s) being utilized.

CES recommendations must be followed for optimum moisture content and levels as well as methods and techniques to monitor and/or determine moisture content and levels.

Avoid fermentation and seepage losses of digestible dry matter from direct cut hay crop silage (moisture content >70%) by treatment with chemical preservatives or add dry feedstuffs.

For optimal dry hay quality, rake hay at 30 to 40 percent moisture and ted or invert swaths when moisture is above 40 percent.

To preserve forage quality and quantity, bale field cured hay at 15 – 20 percent moisture and bale force air-dried hay and 20 – 35 percent moisture.

**Length of Cut.** When harvested for ensilage forage will be chopped to a size appropriate for type of storage structure used and optimal effective fiber. The length of chop selected will allow adequate packing to produce the anaerobic conditions necessary to ensure the proper ensiling process.

A shorter chop length on very dry silage may help to ensure good packing and adequate silage density.

**Stubble Height.** Cut forage plants at a height that will promote the vigor and health of the desired species. Cutting heights will provide adequate residual leaf area; adequate numbers of terminal, basal or auxiliary tillers or buds; insulation from extreme heat or cold;

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and/or unsevered stem bases that store food reserves needed for full, vigorous recovery. Follow CES recommendations for proper stubble heights to avoid winterkill of forage species in cold climates.

**Contaminants.** Forage shall not contain contaminants that can cause illness or death to the animal being fed or rejection of the offered forage. Check CES contaminant notices, cautions, and recommendations for the specific harvest site location and area.

**Additional Criteria to Improve or Maintain Stand Life, Plant Vigor and Forage Species Mix**

**Stage of Maturity and Harvest Interval.** Cut forage plants at a stage of maturity or harvest interval range that will provide adequate food reserves and/or basal or auxiliary tillers or buds for regrowth and/or reproduction to occur without loss of plant vigor.

Cut reseeding annuals at a stage of maturity and frequency that ensures the production of ample viable seed or carryover of hard seed to maintain desired stand density.

If plants show signs of short-term environmental stress, harvests will be adjusted in a manner that encourages the continued health and vigor of the stand. Follow CES recommendations in these cases.

Manipulate timing and cutting heights of harvest to ensure germination and establishment of reseeding or seeded annuals.

**Additional Criteria for Use as a Nutrient Uptake Tool**

Employ a harvest regime that utilizes the maximum amount of available or targeted nutrients. Using this practice for this purpose may require more frequent harvests to increase uptake instead of managing for stand longevity.

**Additional Criteria to Control Disease, Insect, Weed and Invasive Plant Infestations**

Follow CES guidelines when available for control of disease, insect, weed and invasive plant infestations to forage.

Schedule harvest periods to control disease, insect, and weed infestations. When a

pesticide is used to control disease, insects or weeds, adhere to the specified days to harvest period stated on the pesticide label. Evaluate pest management options by planning conservation practice standard Pest Management (595) for all forage areas to be harvested. Also plan and schedule removal of invasive plants and noxious weeds.

Lessen incidence of disease, insect damage, and weed infestation by managing harvests to maintain a full, vigorous, dense forage stand.

Cut forages after dew, rain, or irrigation water on the leaves has evaporated.

**Additional Criteria to Improve Wildlife Habitat Values**

If client objectives include providing suitable habitat for desired wildlife specie(s) then appropriate harvest schedule(s), cover patterns, and minimum plant heights to provide suitable habitat for the desired specie(s) should be implemented and maintained.

Time harvests to benefit the desired wildlife species by following state guidelines.

Coordinate this practice with conservation practice standard Upland Wildlife Habitat Management (645) and accompanying job sheets.

**CONSIDERATIONS**

Where applicable coordinate this practice with NRCS practice standard Prescribed Grazing (528).

When nutrients or other soil amendments are applied coordinate forage harvests with NRCS practice standard Nutrient Management (590) and/or Waste Utilization (633) as appropriate. An excess or improper balance of nutrients such as nitrogen can produce plant material that causes toxicity in some animals.

Produce stored forages of the quality needed for optimum performance of the animal being fed. Legume forages too low in fiber and lead to metabolic disorders in ruminants and an economic loss to the producer due to lowered animal performance. Consider analyzing harvested forages for feed quality. Coordinate this practice with NRCS practice standard Feed Management (592).

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Direct cut grass and legume silage can create silage leachate (seepage) in storage. Consider use of practice standards Runoff Management System (570) and Waste Storage Facility (313).

In conjunction with harvest options, consider storage and feeding options that will retain acceptable forage quality and minimize digestible dry matter loss.

Where weather conditions make it difficult to harvest the desired quality of forage consider use of mechanical or chemical conditioners, forced air barn curing and/or ensile.

Consider delaying harvest if prolonged or heavy precipitation is forecast that would reduce forage quality.

In regions where rainfall and/or humidity levels cause unacceptable forage quality losses consider green chopping or ensiling the forage to reduce or eliminate field drying time. Other options are: the use of desiccants, preservatives, or macerating implements to reduce field-drying time.

To reduce safety hazards, avoid operating harvesting and hauling equipment on field slopes over 25 percent, particularly on cross slope traffic patterns.

Consider Harvesting Forages in the afternoon to optimize water soluble carbohydrates and nutritional quality.

#### PLANS AND SPECIFICATIONS

Place the detailed specifications in a site-specific job or design sheet or in the practice narrative in the conservation plan.

Plans and Specifications must include as minimum for the forage harvest operations:

1. Goals, objectives, specific purpose (such as high forage quantity and quality or nutrient uptake, etc.)
2. Forage species to be harvested  
By each dominant forage species harvested show:
  3. Method of harvest
  4. Stage of maturity
  5. Optimal harvest moisture content

6. Length of cut
7. Stubble height to be left
8. Harvest interval including late harvest if applicable
9. Contaminant avoidance recommendations.

These plans and specifications shall be available through appropriate job sheets and other materials for applying the practice to achieve its intended purpose.

#### OPERATION AND MAINTENANCE

Before forage harvest, clear fields of debris that could damage machinery or if ingested by livestock, lead to sickness (for example, hardware disease) or death.

Operate all forage harvesting equipment at the optimum settings and speeds to minimize loss of leaves.

To control forage plant diseases, insects, and movement of weeds, clean harvesting equipment after harvest and before storing.

Set shear-plate on forage chopper to the proper theoretical cut for the crop being harvested. Keep knives well sharpened. Do not use re-cutters or screens unless forage moisture levels fall below recommended levels for optimum chopping action.

Follow all agricultural equipment manufacturer's safety measures when operating forage harvesting equipment.

Regardless of silage/haylage storage method, ensure good compaction and an airtight seal to exclude oxygen and mold or bacterial formations.

Dispose of the plastic wrap or bags used to store forage in an environmentally sound manner.

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**April 2010**

## NATURAL RESOURCES CONSERVATION SERVICE CONSERVATION PRACTICE STANDARD

### NUTRIENT MANAGEMENT

(Ac.)

CODE 590

#### DEFINITION

Managing the amount, source, placement, form and timing of the application of plant nutrients and soil amendments.

#### PURPOSE

- To budget and supply nutrients for plant production.
- To properly utilize manure or organic by-products as a plant nutrient source.
- To minimize agricultural nonpoint source pollution of surface and ground water resources.
- To protect air quality by reducing nitrogen emissions (ammonia and NO<sub>x</sub> compounds) and the formation of atmospheric particulates.
- To maintain or improve the physical, chemical and biological condition of soil.

#### CONDITIONS WHERE PRACTICE APPLIES

This practice applies to all lands where plant nutrients and soil amendments are applied.

#### CRITERIA

##### General Criteria Applicable to All Purposes

A nutrient budget for nitrogen, phosphorus, and potassium shall be developed that considers all potential sources of nutrients including, but not limited to animal manure and organic by-products, waste water, commercial fertilizer, crop residues, legume credits, and irrigation water.

Realistic yield goals shall be established based on soil productivity information, historical yield data, climatic conditions, level of management and/or local research on similar soil, cropping systems, and soil and manure/organic by-products tests.

For new crops or varieties, industry yield recommendations may be used until documented yield information is available.

Plans for nutrient management shall specify the source, amount, timing and method of application of nutrients on each field to achieve realistic production goals, while minimizing movement of nutrients and other potential contaminants to surface and/or ground waters.

Areas contained within established minimum application setbacks (e.g., sinkholes, wells, gullies, ditches, surface inlets or rapidly permeable soil areas) shall not receive direct application of nutrients.

The amount of nutrients lost to erosion, runoff, irrigation and drainage, shall be addressed, as needed.

**Soil and Tissue Sampling and Laboratory Analyses (Testing).** Nutrient planning shall be based on current soil and tissue (where used as a supplement) test results developed in accordance with Land Grant University guidance, or industry practice if recognized by the Land Grant University. Current soil tests are those that are no older than five years.

Soil and tissue samples shall be collected and prepared according to the Land Grant University guidance or standard industry practice. Soil and tissue test analyses shall be performed by laboratories that are accepted in one or more of the following:

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- Laboratories successfully meeting the requirements and performance standards of the North American Proficiency Testing Program (NAPT) under the auspices of the Soil Science Society of America, or
- State recognized program that considers laboratory performance and proficiency to assure accuracy of soil test results.

Soil and tissue testing shall include analyses for any nutrients for which specific information is needed to develop the nutrient plan. Request analyses pertinent to monitoring or amending the annual nutrient budget, e.g. pH, electrical conductivity (EC), soil organic matter, nitrogen, phosphorus and potassium.

**Nutrient Application Rates.** Soil amendments shall be applied, as needed, to adjust soil pH to an adequate level for crop nutrient availability and utilization.

Recommended nutrient application rates shall be based on Land Grant University recommendations (and/or industry practice when recognized by the university) that consider current soil test results, realistic yield goals and management capabilities. If the Land Grant University does not provide specific recommendations, application shall be based on realistic yield goals and associated plant nutrient uptake rates.

The planned rates of nutrient application, as documented in the nutrient budget, shall be determined based on the following guidance:

- **Nitrogen Application** - Planned nitrogen application rates shall match the recommended rates as closely as possible, except when manure or organic by-products are a source of nutrients. When manure or organic by-products are a source of nutrients, see "Additional Criteria" below.
- **Phosphorus Application** - Planned phosphorus application rates shall match the recommended rates as closely as possible, except when manure or organic by-products are sources of nutrients. When manure or organic by-products are a source of nutrients, see "Additional Criteria" below.

- **Potassium Application** - Potassium shall not be applied in situations in which excess (greater than soil test potassium recommendation) causes unacceptable nutrient imbalances in crops or forages. When forage quality is an issue associated with excess potassium application, state standards shall be used to set forage quality guidelines.
- **Other Plant Nutrients** - The planned rates of application of other nutrients shall be consistent with Land Grant University guidance or industry practice if recognized by the Land Grant University in the state.
- **Starter Fertilizers** - When starter fertilizers are used, they shall be included in the overall nutrient budget, and applied in accordance with Land Grant University recommendations, or industry practice if recognized by the Land Grant University within the state.

**Nutrient Application Timing.** Timing and method of nutrient application (particularly nitrogen) shall correspond as closely as possible with plant nutrient uptake characteristics, while considering cropping system limitations, weather and climatic conditions, risk assessment tools (e.g., leaching index, P index) and field accessibility.

**Nutrient Application Methods.** Application methods to reduce the risk of nutrient transport to surface and ground water, or into the atmosphere shall be employed.

To minimize nutrient losses:

- Apply nutrient materials uniformly to application area(s).
- Nutrients shall not be applied to frozen, snow-covered or saturated soil if the potential risk for runoff exists.
- Nutrients shall be applied considering the plant growth habits, irrigation practices, and other conditions so as to maximize availability to the plant and minimize the risk of runoff, leaching, and volatilization losses.
- Nutrient applications associated with irrigation systems shall be applied in a

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manner that prevents or minimizes resource impairment.

**Conservation Management Unit (CMU) Risk Assessment.** In areas with identified or designated nutrient related water quality impairment, a CMU specific risk assessment of the potential for nutrient transport from the area shall be completed.

States that utilize a threshold prescreening procedure to trigger CMU risk assessment shall follow approved procedures as recommended by the respective state or Land Grant University.

Use an appropriate nutrient risk assessment tool for the nutrient in question (e.g., leaching index, phosphorus index) or other state recognized assessment tool.

**Additional Criteria Applicable to Manure and Organic By-Products or Biosolids Applied as a Plant Nutrient Source**

When animal manures or organic by-products are applied, a risk assessment of the potential for nutrient transport from the CMU shall be completed to adjust the amount, placement, form and timing of application of nutrient sources, as recommended by the respective state or Land Grant University.

Nutrient values of manure and organic by-products (excluding sewage sludge or biosolids) shall be determined prior to land application. Samples will be taken and analyzed with each hauling/emptying cycle for a storage/treatment facility. Manure sampling frequency may vary based on the operation's manure handling strategy and spreading schedule. If there is no prior sampling history, the manure shall be analyzed at least annually for a minimum of three consecutive years. A cumulative record shall be developed and maintained until a consistent (maintaining a certain nutrient concentration with minimal variation) level of nutrient values is realized. The average of results contained in the operation's cumulative manure analyses history shall be used as a basis for nutrient allocation to fields. Samples shall be collected and prepared according to Land Grant University guidance or industry practice.

In planning for new operations, acceptable "book values" recognized by the NRCS and/or the Land Grant University may be used if they accurately estimate nutrient output from the proposed operation (e.g., NRCS Agricultural Waste Management Field Handbook).

Biosolids (sewage sludge) shall be applied in accordance with USEPA regulations. (40 CFR Parts 403 (Pretreatment) and 503 (Biosolids) and other state and/or local regulations regarding the use of biosolids as a nutrient source.

**Manure and Organic By-Product Nutrient Application Rates.** Manure and organic by-product nutrient application rates shall be based on nutrient analyses procedures recommended by the respective state or Land Grant University. As indicated above, "book values" may be used in planning for new operations. At a minimum, manure analyses shall identify nutrient and specific ion concentrations, percent moisture, and percent organic matter. Salt concentration shall be monitored so that manure applications do not cause plant damage or negatively impact soil quality.

The application rate (in/hr) of liquid materials applied shall not exceed the soil intake/infiltration rate and shall be adjusted to minimize ponding and to avoid runoff. The total application shall not exceed the field capacity of the soil and shall be adjusted, as needed, to minimize loss to subsurface tile drains.

The planned rates of nitrogen and phosphorus application recorded in the plan shall be determined based on the following guidance:

**Nitrogen Application Rates**

- When manure or organic by-products are used, the nitrogen availability of the planned application rates shall match plant uptake characteristics as closely as possible, taking into consideration the timing of nutrient application(s) in order to minimize leaching and atmospheric losses.
- Management activities and technologies shall be used that effectively utilize mineralized nitrogen and that minimize nitrogen losses

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through denitrification and ammonia volatilization.

- Manure or organic by-products may be applied on legumes at rates equal to the estimated removal of nitrogen in harvested plant biomass.
- When the nutrient management plan component is being implemented on a phosphorus basis, manure or organic by-products shall be applied at rates consistent with a phosphorus limited application rate. In such situations, an additional nitrogen application, from non-organic sources, may be required to supply, but not exceed, the recommended amounts of nitrogen in any given year.

#### Phosphorus Application Rates

- When manure or organic by-products are used, the planned rates of phosphorus application shall be consistent with any one of the following options:
  - ◇ Phosphorus Index (PI) Rating. Nitrogen-based manure application on Low or Medium Risk Sites; phosphorus-based or no manure application on High and Very High Risk Sites.\*\*
  - ◇ Soil Phosphorus Threshold Values. Nitrogen-based manure application on sites on which the soil test phosphorus levels are below the threshold values; Phosphorus-based or no manure application on sites on which soil phosphorus levels equal or exceed threshold values.\*\*
  - ◇ Soil Test. Nitrogen-based manure application on sites for which the soil test recommendation calls for phosphorus application; phosphorus-based or no manure application on sites for which the soil test recommendation calls for no phosphorus application. ‡

\*\* Acceptable phosphorus-based manure application rates shall be determined as a function

of soil test recommendation or estimated phosphorus removal in harvested plant biomass.

Guidance for developing these acceptable rates is found in the NRCS General Manual, Title 190, Part 402 (Ecological Sciences, Nutrient Management, Policy), and the National Agronomy Manual, Section 503 (to be developed).

- The application of phosphorus applied as manure may be made at a rate equal to the recommended phosphorus application or estimated phosphorus removal in harvested plant biomass for the crop rotation or multiple years in the crop sequence. When such applications are made, the application rate shall:
  - ◇ Not exceed the recommended nitrogen application rate during the year of application, or
  - ◇ Not exceed the estimated nitrogen removal in harvested plant biomass during the year of application when there is no recommended nitrogen application.
  - ◇ Not be made on sites considered vulnerable to off-site phosphorus transport unless appropriate conservation practices, best management practices or management activities are used to reduce the vulnerability.

**Heavy Metal Monitoring.** When sewage sludge (biosolids) is applied, the accumulation of potential pollutants (including arsenic, cadmium, copper, lead, mercury, selenium, and zinc) in the soil shall be monitored in accordance with the US Code, Reference 40 CFR, Parts 403 and 503, and/or any applicable state and local laws or regulations.

#### Additional Criteria to Protect Air Quality by Reducing Nitrogen and/or Particulate Emissions to the Atmosphere

In areas with an identified or designated nutrient management related air quality concern, any component(s) of nutrient

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management (i.e., amount, source, placement, form, timing of application) identified by risk assessment tools as a potential source of atmospheric pollutants shall be adjusted, as necessary, to minimize the loss(es).

When tillage can be performed, surface applications of manure and fertilizer nitrogen formulations that are subject to volatilization on the soil surface (e.g., urea) shall be incorporated into the soil within 24 hours after application.

When manure or organic by-products are applied to grassland, hayland, pasture or minimum-till areas the rate, form and timing of application(s) shall be managed to minimize volatilization losses.

When liquid forms of manure are applied with irrigation equipment, operators will select weather conditions during application that will minimize volatilization losses.

Operators will handle and apply poultry litter or other dry types of animal manures when the potential for wind-driven loss is low and there is less potential for transport of particulates into the atmosphere.

Weather and climatic conditions during manure or organic by-product application(s) shall be recorded and maintained in accordance with the operation and maintenance section of this standard.

#### **Additional Criteria to Improve the Physical, Chemical and Biological Condition of the Soil**

Nutrients shall be applied and managed in a manner that maintains or improves the physical, chemical and biological condition of the soil.

Minimize the use of nutrient sources with high salt content unless provisions are made to leach salts below the crop root zone.

To the extent practicable nutrients shall not be applied when the potential for soil compaction and rutting is high.

#### **CONSIDERATIONS**

The use of management activities and technologies listed in this section may improve

both the production and environmental performance of nutrient management systems.

The addition of these management activities, when applicable, increases the management intensity of the system and is recommended in a nutrient management system.

Action should be taken to protect National Register listed and other eligible cultural resources.

The nutrient budget should be reviewed annually to determine if any changes are needed for the next planned crop.

For sites on which there are special environmental concerns, other sampling techniques may be appropriate. These include soil profile sampling for nitrogen, Pre-Sidedress Nitrogen Test (PSNT), Pre-Plant Soil Nitrate Test (PPSN) or soil surface sampling for phosphorus accumulation or pH changes.

Additional practices to enhance the producer's ability to manage manure effectively include modification of the animal's diet to reduce the manure nutrient content, or utilizing manure amendments that stabilize or tie-up nutrients.

Soil test information should be no older than one year when developing new plans, particularly if animal manures are to be used as a nutrient source.

Excessive levels of some nutrients can cause induced deficiencies of other nutrients.

If increases in soil phosphorus levels are expected, consider a more frequent (annual) soil testing interval.

To manage the conversion of nitrogen in manure or fertilizer, use products or materials (e.g. nitrification inhibitors, urease inhibitors and slow or controlled release fertilizers) that more closely match nutrient release and availability for plant uptake. These materials may improve the nitrogen use efficiency (NUE) of the nutrient management system by reducing losses of nitrogen into water and/or air.

#### ***Considerations to Minimize Agricultural Nonpoint Source Pollution of Surface and Ground Water.***

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Erosion control and runoff reduction practices can improve soil nutrient and water storage, infiltration, aeration, tilth, diversity of soil organisms and protect or improve water and air quality (Consider installation of one or more NRCS FOTG, Section IV – Conservation Practice Standards).

Cover crops can effectively utilize and/or recycle residual nitrogen.

Apply nutrient materials uniformly to the application area. Application methods and timing that reduce the risk of nutrients being transported to ground and surface waters, or into the atmosphere include:

- Split applications of nitrogen to provide nutrients at the times of maximum crop utilization,
- Use stalk-test to minimize risk of over applying nitrogen in excess of crop needs.
- Avoid winter nutrient application for spring seeded crops,
- Band applications of phosphorus near the seed row,
- Incorporate surface applied manures or organic by-products as soon as possible after application to minimize nutrient losses,
- Delay field application of animal manures or organic by-products if precipitation capable of producing runoff and erosion is forecast within 24 hours of the time of the planned application.

***Considerations to Protect Air Quality by Reducing Nitrogen and/or Particulate Emissions to the Atmosphere.***

Odors associated with the land application of manures and organic by-products can be offensive to the occupants of nearby homes. Avoid applying these materials upwind of occupied structures when residents are likely to be home (evenings, weekends and holidays).

When applying manure with irrigation equipment, modifying the equipment can reduce the potential for volatilization of nitrogen from the time the manure leaves the application equipment until it reaches the surface of the soil (e.g., reduced pressure,

drop down tubes for center pivots). N volatilization from manure in a surface irrigation system will be reduced when applied under a crop canopy.

When planning nutrient applications and tillage operations, encourage soil carbon buildup while discouraging greenhouse gas emissions (e.g., nitrous oxide N<sub>2</sub>O, carbon dioxide CO<sub>2</sub>).

Nutrient applications associated with irrigation systems should be applied in accordance with the requirements of Irrigation Water Management (Code 449).

CAFO operations seeking permits under USEPA regulations (40 CFR Parts 122 and 412) should consult with their respective state permitting authority for additional criteria.

**PLANS AND SPECIFICATIONS**

Plans and specifications for nutrient management shall be in keeping with this standard and shall describe the requirements for applying the practice to achieve its intended purpose(s), using nutrients to achieve production goals and to prevent or minimize resource impairment.

Nutrient management plans shall include a statement that the plan was developed based on requirements of the current standard and any applicable Federal, state, or local regulations, policies, or programs, which may include the implementation of other practices and/or management activities. Changes in any of these requirements may necessitate a revision of the plan.

The following components shall be included in the nutrient management plan:

- aerial site photograph(s) or site map(s), and a soil survey map of the site,
- location of designated sensitive areas or resources and the associated, nutrient management restriction,
- current and/or planned plant production sequence or crop rotation,
- results of soil, water, manure and/or organic by-product sample analyses,
- results of plant tissue analyses, when used for nutrient management,

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- realistic yield goals for the crops,
- complete nutrient budget for nitrogen, phosphorus, and potassium for the crop rotation or sequence,
- listing and quantification of all nutrient sources,
- CMU specific recommended nutrient application rates, timing, form, and method of application and incorporation, and
- guidance for implementation, operation, maintenance, and recordkeeping.

If increases in soil phosphorus levels are expected, the nutrient management plan shall document:

- the soil phosphorus levels at which it may be desirable to convert to phosphorus based planning,
- results of appropriate risk assessment tools to document the relationship between soil phosphorus levels and potential for phosphorus transport from the field,
- the potential for soil phosphorus drawdown from the production and harvesting of crops, and
- management activities or techniques used to reduce the potential for phosphorus loss.

#### OPERATION AND MAINTENANCE

The owner/client is responsible for safe operation and maintenance of this practice including all equipment. Operation and maintenance addresses the following:

- periodic plan review to determine if adjustments or modifications to the plan are needed. As a minimum, plans will be reviewed and revised with each soil test cycle.
- significant changes in animal numbers and/or feed management will necessitate additional manure sampling and analyses to establish a revised average nutrient content.
- protection of fertilizer and organic by-product storage facilities from weather and accidental leakage or spillage.

- calibration of application equipment to ensure uniform distribution of material at planned rates.
- documentation of the actual rate at which nutrients were applied. When the actual rates used differ from the recommended and planned rates, records will indicate the reasons for the differences.
- Maintaining records to document plan implementation. As applicable, records include:
  - Soil, plant tissue, water, manure, and organic by-product analyses resulting in recommendations for nutrient application,
  - quantities, analyses and sources of nutrients applied,
  - dates and method(s) of nutrient applications,
  - weather conditions and soil moisture at the time of application; lapsed time to manure incorporation, rainfall or irrigation event.
  - crops planted, planting and harvest dates, yields, and crop residues removed,
  - dates of plan review, name of reviewer, and recommended changes resulting from the review.

Records should be maintained for five years; or for a period longer than five years if required by other Federal, state or local ordinances, or program or contract requirements.

Workers should be protected from and avoid unnecessary contact with plant nutrient sources. Extra caution must be taken when handling ammoniacal nutrient sources, or when dealing with organic wastes stored in unventilated enclosures.

Material generated from cleaning nutrient application equipment should be utilized in an environmentally safe manner. Excess material should be collected and stored or field applied in an appropriate manner.

Nutrient containers should be recycled in compliance with state and local guidelines or regulations.

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## APPENDIX II Factors used to convert metric units to English units

**APPENDIX TABLE II.** Factors used to convert metric values to English units.

From	To	Multiply by
<b>Length</b>		
Kilometer, km	Mile, mi	0.621
Meter, m	Yard, yd	1.094
Meter, m	Foot, ft	3.280
Millimeter, mm	Inch, in	0.039
<b>Area</b>		
Hectare, ha	Acre	2.470
Square meter, m <sup>2</sup>	Square foot, ft <sup>2</sup>	10.760
<b>Volume</b>		
Liter, L	Quart, qt	1.057
Liter, L	Cubic foot, ft <sup>3</sup>	0.035
<b>Mass</b>		
Gram, g	Pound, lb	0.0022
Gram, g	Ounce, oz	0.0352
Kilogram, kg	Pound, lb	2.205
Kilogram, kg	Ton (US, 2000 lb), ton	0.0011
Megagram, Mg (tonne)	Ton (US, 2000 lb), ton	1.102
<b>Yield and Rate</b>		
kg per ha, kg ha <sup>-1</sup>	lb per acre, lb acre <sup>-1</sup>	0.893
Mg per ha, Mg ha <sup>-1</sup>	lb per acre, lb acre <sup>-1</sup>	893.0
Tonne per ha, Mg (tonne)	Ton (2000 lb) per acre	0.446
Meter per second, m sec <sup>-1</sup>	Mile per hour, mph	2.24

**APPENDIX TABLE III.** List of common and scientific names for species mentioned in the book. Scientific names are according to the USDA-NRCS PLANTS database (<http://plants.usda.gov>) except those with an asterisk for which the USDA Germplasm Resources Information Network (GRIN; <http://www.ars-grin.gov/>) was consulted.

### Crop species

1. Barley (*Hordeum vulgare* L.)
2. Canola (*Brassica campestris* L.)
3. Corn (*Zea mays* L.)
4. Cotton (*Gossypium hirsutum* L.)
5. Oat (*Avena sativa* L.)
6. Peanut (*Arachis hypogaea* L.)
7. Rye (*Secale cereale* L.)
8. Soybean (*Glycine max* [L.] Merr.)
9. Sunflower (*Helianthus* spp.)
10. Triticale (x *Triticosecale rimpaii* Wittmack)
11. Wheat (*Triticum aestivum* L.)
12. Winter pea, pea (*Pisum sativum* L.)
13. Winter rye (*Secale cereale* L.)

### Cool-season annual grasses

14. Annual poa (*Poa annua* L.)
15. Annual ryegrass (*Lolium multiflorum* Lam.)\*
16. Black oat (*Avena strigosa* Schreb.)
17. Italian ryegrass (*Lolium multiflorum* Lam.)\*
18. Short-rotation (hybrid) ryegrass (*Lolium x hybridum* Hausskn.)

### Warm-season annual grasses

19. Broadleaf signalgrass (*Urochloa platyphylla* [Munro ex C. Wright] R.D. Webster)
20. Crabgrass (*Digitaria* spp)
21. Fall panicum (*Panicum dichotomiflorum* Michx.)\*
22. Pearl millet (*Pennisetum glaucum* [L.] R. Br.)
23. Sandbur (*Cenchrus* spp.)
24. Setaria (*Setaria sphacelata* [Schumach.] Stapf & C.E. Hubb.)
25. Sorghum-sudangrass (*Sorghum bicolor* [L.] Moench nothosubsp. *drummondii* (Steud.) de Wet ex Davidse)\*
26. Sudangrass (*Sorghum bicolor* [L.] Moench ssp. *drummondii* [Nees ex Steud.] de Wet & Harlan)
27. Teff (*Eragrostis tef* [Zuccagni] Trotter)
28. Texas panicum (*Urochloa texana* [Buckley] R.D. Webster)\*

### Warm-season perennial grasses

29. Bahiagrass (*Paspalum notatum* Flueggé)
30. Bermudagrass (*Cynodon dactylon* [L.] Pers.)
31. Big bluestem (*Andropogon gerardii* Vitman)
32. Blue grama (*Bouteloua gracilis* [Willd. ex Kunth] Lag. ex Griffiths)
33. Brachiariagrass cv. Mulato (*Brachiaria* spp.)
34. Buffalograss (*Bouteloua dactyloides* [Nutt.] J.T. Columbus)
35. Buffelgrass (*Pennisetum ciliare* [L.] Link)

36. Caucasian bluestem (*Bothriochloa bladhii* [Retz.] S.T. Blake)
37. Creeping signalgrass (*Urochloa humidicola* (Rendle) Morrone & Zuloaga)
38. Dallisgrass (*Paspalum dilatatum* Poir.)
39. Digitgrass (*Digitaria eriantha* Steud.)
40. Eastern gamagrass (*Tripsacum dactyloides* L.)
41. Energy cane, sugarcane (*Saccharum* spp. L.)
42. Giant reed (*Arundo donax* L.)
43. Green needlegrass (*Nassella viridula* [Trin.] Barkworth)
44. Guineagrass (*Urochloa maxima* (Jacq.) R. Webster)
45. Indiangrass (*Sorghastrum nutans* [L.] Nash)
46. Johnsongrass (*Sorghum halepense* [L.] Pers.)
47. Kikuyugrass (*Pennisetum clandestinum* Hochst. ex Chiov.)
48. Kleingrass (*Panicum coloratum* L.)
49. Lehmann lovegrass (*Eragrostis lehmanniana* Nees.)
50. Limpograss (*Hemarthria altissima* [Poir.] Stapf et C.E. Hubb.)
51. Miscanthus (*Miscanthus x giganteus* Greef et Deu)
52. Old world bluestem (*Bothriochloa* spp.)
53. Palisadegrass (*Urochloa brizantha* [Hochst. ex A. Rich.] R. Webster)
54. Stargrass (*Cynodon plectostachyus* [K. Schum.] Pilg.)
55. Switchgrass (*Panicum virgatum* L.)
56. Vaseygrass (*Paspalum urvillei* Steud.)
57. Weeping lovegrass (*Eragrostis curvula* [Schrud.] Nees)
58. Wilman lovegrass (*Eragrostis superba* Peyr.)

### Cool-season perennial grasses (and sedges)

59. Creeping foxtail (*Alopecurus arundinaceus* Poir.)
60. Crested wheatgrass (*Agropyron cristatum* [L.] Gaertn.)
61. Festulolium (x *Festulolium loliaceum* [Huds.] P. Fourn.)
62. Grazing brome grass (*Bromus stamineus* Desv.)
63. Intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth & D.R. Dewey)
64. Kentucky bluegrass (*Poa pratensis* L.)
65. Meadow brome grass (*Bromus biebersteinii* Roem. & Schult.)
66. Orchardgrass (*Dactylis glomerata* L.)
67. Perennial ryegrass (*Lolium perenne* L.)
68. Phalaris (*Phalaris aquatica* L.)

APPENDIX TABLE III. continued.

69. Prairiegrass (rescuegrass) (*Bromus catharticus* Vahl)
70. Purple nutsedge (*Cyperus rotundus* L.)
71. Quackgrass (*Elymus repens* [L.] Gould)
72. Red oatgrass (*Themeda triandra* Forsk.)
73. Reed canarygrass (*Phalaris arundinacea* L.)
74. Rough fescue (*Festuca campestris* Rydb.)
75. Russian wildrye (*Psathyrostachys juncea* [Fisch.] Nevski)
76. Slender wheatgrass (*Elymus trachycaulus* [Link] Gould ex Shinnars)
77. Smooth brome grass (*Bromus inermis* Leyss.)
78. Tall fescue (*Schedonorus phoenix* [Scop.] Holub; syn, *Lolium arundinaceum* [Schreb.] S.J. Darbyshire; formerly *Festuca arundinacea* Schreb.)
79. Tall wheatgrass (*Thinopyrum ponticum* [Podp.] Z.-W. Liu & R.-C. Wang)
80. Thickspike wheatgrass (*Elymus lanceolatus* [Scribn. & J.G. Sm.] Gould)
81. Timothy (*Phleum pratense* L.)
82. Yellow nutsedge (*Cyperus esculentus* L.)
106. Striate lespedeza (*Kummerowia striata* [Thunb.] Schindl.)
107. Sulla (*Hedysarum coronarium* L.)
108. Tickclover (*Desmodium* spp.)
109. Tropical kudzu (*Pueraria phaseoloides* [Roxb.] Benth.)
110. Velvet bean (*Mucuna pruriens* [L.] DC.)
111. White sweetclover (*Melilotus albus* Medik.)
112. Yellow sweetclover (*Melilotus officinalis* [L.] Lam.)

### Clovers

113. Alsike clover (*Trifolium hybridum* L.)
114. Arrowleaf clover (*Trifolium vesiculosum* Savi)
115. Balansa clover (*Trifolium michelianum* Savi ssp. *balansae* [Boiss.] Ponert)
116. Ball clover (*Trifolium nigrescens* Viv.)
117. Berseem clover (*Trifolium alexandrinum* L.)
118. Buffalo clover (*Trifolium reflexum* L.)
119. Crimson clover (*Trifolium incarnatum* L.)
120. Kura clover (*Trifolium ambiguum* M. Bieb.)
121. Persian clover (*Trifolium resupinatum* L.)
122. Red clover (*Trifolium pratense* L.)
123. Rose clover (*Trifolium hirtum* All.)
124. Strawberry clover (*Trifolium fragiferum* L.)
125. Subterranean clover (*Trifolium subterraneum* L.)
126. White clover (or ladino clover) (*Trifolium repens* L.)

### Vetches

127. Cicer milkvetch (*Astragalus cicer* L.)
128. Crownvetch (*Securigera varia* [L.] Lassen)
129. Hairy vetch (*Vicia villosa* Roth subsp. *villosa*)\*
130. Deervetch (*Vicia ludoviciana* Nutt.)
131. Woollypod vetch (*Vicia villosa* Roth ssp. *varia* [Host] Corb.)\*

### Medics

132. Alfalfa (*Medicago sativa* L.)
133. Barrel medic (*Medicago truncatula* Gaertn.)
134. Black medic (*Medicago lupulina* L.)
135. Burr medic (*Medicago polymorpha* L.)
136. Little burr medic (*Medicago minima* L.)
137. Rigid medic (*Medicago rigiduloides* E. Small)\*
138. Tifton burr medic (*Medicago rigidula* [L.] All.)

### Nonleguminous forbs

139. Annual ragweed (*Ambrosia artemisiifolia* L.)
140. Chicory (*Cichorium intybus* L.)
141. Multiflora rose (*Rosa multiflora* Thunb.)
142. Nodding thistle (*Carduus nutans* L.)
143. Plantain (*Plantago lanceolata* L.)
144. Turnip (*Brassica rapa* L.)\*

### Legumes (annual and perennial)

83. Aeschynomene (*Aeschynomene americana* L.)
84. Big trefoil (*Lotus pedunculatus* Cav.)
85. Birdsfoot trefoil (*Lotus corniculatus* L.)
86. Cowpea (*Vigna unguiculata* [L.] Walp.)
87. Faba bean (*Vicia faba* L.)
88. Illinois bundleflower (*Desmanthus illinoensis* [Michx.] MacMill. ex B.L. Rob. & Fernald)
89. Korean lespedeza (*Kummerowia stipulacea* [Maxim.] Makino)
90. Kudzu (*Pueraria montana* [Lour.] Merr.)
91. Lablab (*Lablab purpureus* [L.] Sweet)
92. Leadplant (*Amorpha canescens* Pursh)
93. Leucaena (*Leucaena leucocephala* [Lam.] De Wit)
94. Lupin (*Lupinus* spp.)
95. Mungbean (*Vigna radiata* [L.] R. Wilczek)
96. Ovalifolium (*Desmodium ovalifolium* [L.] DC. subsp. *ovalifolium* [Prain] H. Ohashi), *Desmodium adscendens* (Sw.) DC.
97. Partridgepea (*Chamaecrista fasciculata* [Michx.] Greene)
98. Pinto peanut (*Arachis pintoi* Krapov. & W.C. Greg.)
99. Prairie clover (*Dalea* spp.)
100. Purple prairie clover (*Dalea purpurea* Vent.)
101. Rhizoma peanut (*Arachis glabrata* Benth.)
102. Roundhead lespedeza (*Lespedeza capitata* Michx.)
103. Sainfoin (*Onobrychis viciifolia* Scop.)
104. Sericea lespedeza (*Lespedeza cuneata* [Dum. Cours.] G. Don)
105. Siratro (*Macroptilium atropurpureum* [Moc. & Sessé ex DC.] Urb.)

## Animals

145. Black grouse (*Tetrao tetrix*)
146. Brown hare (*Lepus europaeus*)
147. Brown trout (*Salmo trutta*)
148. Cattle (*Bos* sp.)
149. Crested caracaras (*Caracara cheriway*)
150. Deer (*Odocoileus* spp.)
151. Eastern garter snakes (*Thamnophis sirtalis*)
152. Elk (*Cervus elaphus*)
153. Field vole (*Microtus agrestis*)
154. Goat (*Capra hircus*)
155. Grasshopper sparrow (*Ammodramus savannarum*)
156. Horse (*Equus caballus*)
157. Iberian ibex (*Capra pyrenaica* Schinz)
158. Meadow pipit (*Anthus pratensis*)
159. Mottled duck (*Anas fulvigula maculosa*)
160. Northern queen snake (*Regina septemvittata*)
161. Prairie chicken (*Tympanuchus cupido pinnatus*)
162. Sage grouse (*Centrocercus urophasianus*)
163. Sheep (*Ovis aries*)
164. Spur-thighed tortoise (*Testudo graeca*)
165. Upland sandpiper (*Bartramia longicauda*)

## Other (specific bacteria and fungi)

*Campylobacter jejuni*  
*Cryptosporidium parvum*  
*Escherichia coli*  
*Leptospira grippotyphosa*  
*Salmonella java*  
*Salmonella typhimurium*  
*Shigella flexneri*  
*Shigella sonnei*  
Endophyte fungus (*Neotyphodium coenophialum*  
(Morgan-Jones & W. Gams) Glenn, C.W. Bacon & Hanlin)

**APPENDIX TABLE IV.** List of trade names and chemical names of pesticides and other chemicals mentioned in the book.

Common name	Trade name	Chemical name
<b>Herbicides</b>		
2,4-D acid plus dicamba	Outlaw	3,6-dichloromethoxybenzoic acid; 2-ethylhexyl ester of 2,4-dichlorophenoxyacetic acid
2,4-D amine	AgriStar 2,4-D amine 4	2,4-dichlorophenoxyacetic acid
2,4-D amine plus dicamba	Weedmaster	Dicamba (3,6-dichloro-o-anisic acid); 2,4-dichlorophenoxyacetic acid
2,4-D amine plus picloram	Grazon P+D	4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid; (2,4-dichlorophenoxy) acetic acid
2,4-D ester	AgriStar 2,4-D LV4 or LV6	2-ethylhexyl ester of 2,4-dichlorophenoxy acetic acid
2,4-DB	Butyrac	4-(2,4-dichlorophenoxy)butyric acid
Atrazine	Aatrex	2-chloro-4-ethylamino-6-isopropylamino-s-triazine
Benefin	Balan	N-butyl-N-ethyl- $\alpha,\alpha,\alpha$ -trifluoro-2,6-dinitro-p-toluidine
Bromoxynil	Buctril	3,5-dibromo-4-hydroxybenzonitrile
Clethodim	Select	(E)-2-[1-[(3-chloro-2-propenyl)oxy]imino]propyl]-5-[2-ethylthio]propyl-3-hydroxy-2-cyclohexen-1-one
Diuron	Direx	3-[3,4-dichlorophenyl]-1,1-dimethylurea
EPTC	Eptam	S-ethyl dipropylthiocarbamate
Flumioxazin	Chateau	2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propynyl)-2H-1,4-benzox-azin-6-yl]-4,5,6,7-tetrahydro-1H-isoindole-1,3(2H)-dione
Glyphosate	Roundup; Roundup WeatherMax	N-(phosphonomethyl) glycine
Hexazinone	Velpar	3-cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine-2,4(1H,3H)-dione
Imazamox	Raptor	2-[4,5-dihydro-4-methyl-4(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid
Imazapic	Impose	( $\pm$ )-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-methyl-3-pyridinecarboxylic acid.
Imazethapyr	Pursuit/Thunder	( $\pm$ )-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid
Metolachlor	Dual II	2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide
Metribuzin	Sencor	4-amino-6-(1,1-dimethyl)-3-(methylthio)-1,3,4-triazin-5(4H)-one
Nicosulfuron	Accent	2-[[[4,6-dimethoxypyrimidin-2-yl]aminocarbonyl]aminosulfonyl] N,Ndimethyl-3-pyridinecarboxamide
Norflurazon	Solicam	4-chloro-5-(methylamino)-2- $\alpha,\alpha,\alpha$ -trifluoro-m-tolyl)-3-(2H)pyridazinone

APPENDIX TABLE IV. continued.

Common name	Trade name	Chemical name
Paraquat	CycloneMax	1,1'-dimethyl-4,4'-bipyridinium dichloride
Pendamethalin	Prowl	N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine
Pronamide	Kerb	3,5-dichloro-N-(1,1-dimethyl-2-propynyl)benzamide
Quinclorac	Paramount	3,7-dichloro-8-quinolinecarboxylic acid
Sethoxydim	PoastPlus	2-[1-(ethoxyimino)butyl]-5-[2-ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one
Siduron	Tupersan	[1-(2-methylcyclohexyl)-3-phenylurea
Sulfosulfuron	Outrider	1-[4,6-dimethoxypyrimidin-2-yl]-3-[2-ethylsulfonylimidazo[1,2-a]pyridin-3-yl)sulfonylurea
Terbacil	Sinbar	3- <i>tert</i> -butyl-5-chloro-6-methyluracil
Triasulfuron	Amber	1-[2-(2-chloroethoxy)phenyl)sulfonyl-3-(4-methoxy-6-methyl-1,3,5-triazin-2-yl)urea
Trifluralin	Treflan	$\alpha,\alpha,\alpha$ -trifluoro-2,6-dinitro-N,N-dipropyl-p-toluidine
Insecticides		
Carbosulfan		2,3-dihydro-2,2-dimethylbenzofuran-7-yl (dibutylaminothio)methylcarbamate
Furathiocarb		butyl 2,3-dihydro-2,2-dimethylbenzofuran-7-yl N,N'-dimethyl-N,N'-thiodicarbamate
Imidacloprid		1-(6-chloro-3-pyridylmethyl)-N-nitroimidazolidin-2-ylideneamine
Isofenphos		(RS)-(O-ethyl O-2-isopropoxycarbonylphenyl isopropylphosphoramidothioate)
Fungicide		
Mefenoxam (Metalaxyl)	Apron	N-(2,6-dimethylphenyl)-N-(2-methoxyecetyl)-DL-alanine

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